

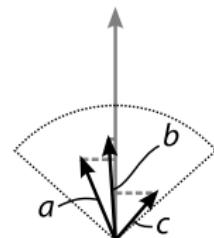
Jets from PHENIX

Yue Shi Lai, for the PHENIX Collaboration

Columbia University and Nevis Laboratories

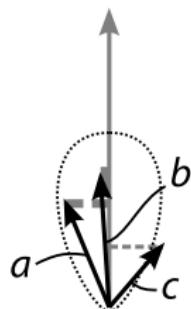
JET Symposium

Gaussian filter



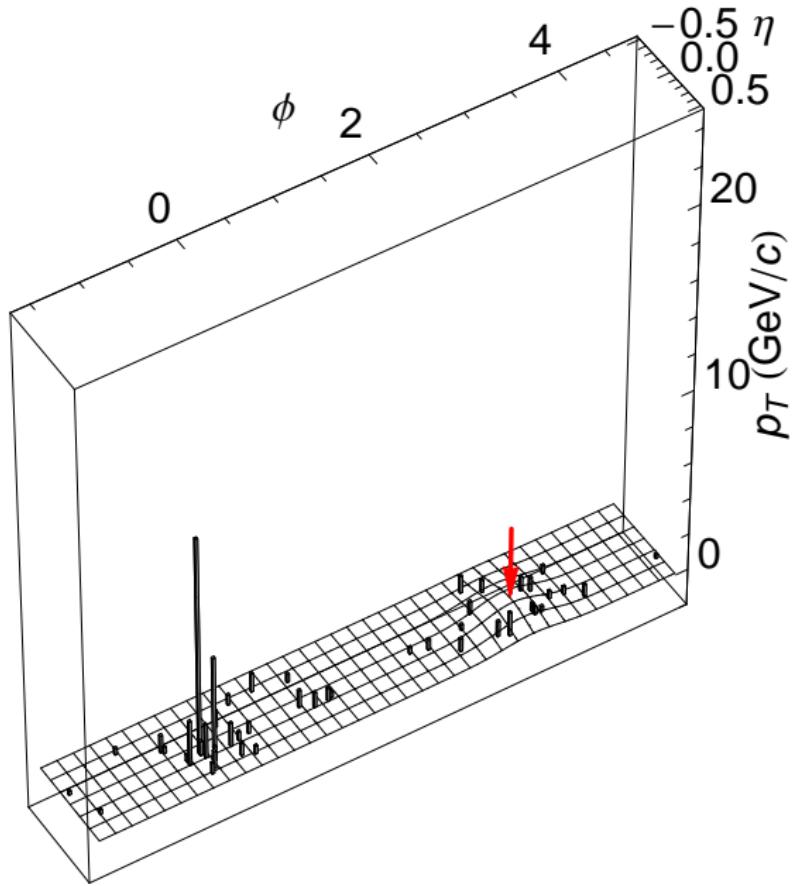
Cone

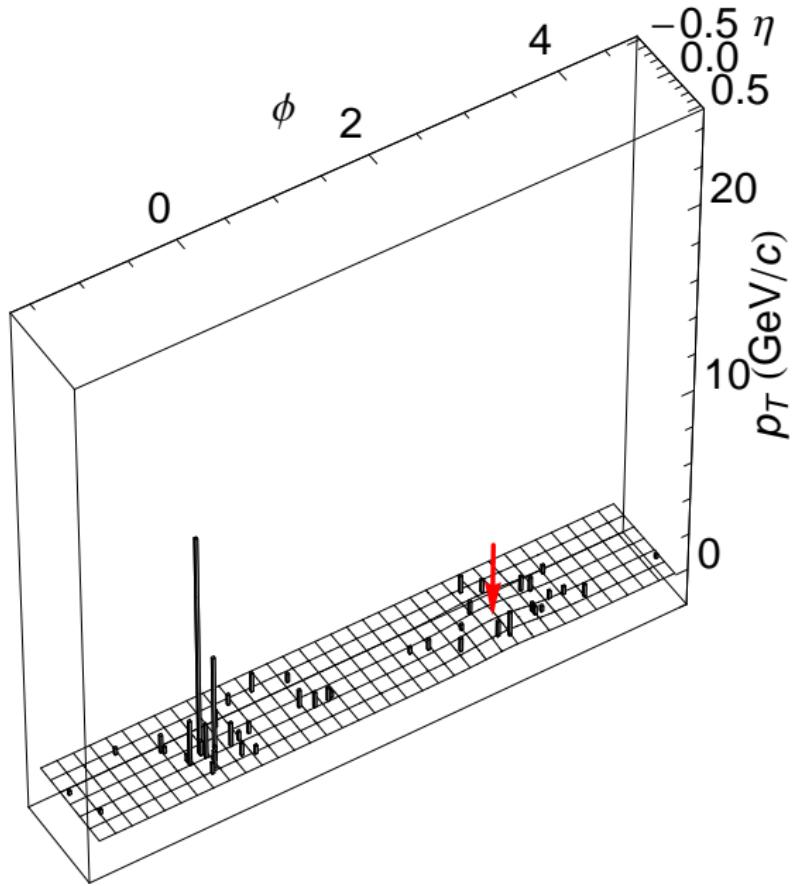
$$\iint_{\mathbb{R} \times S^1} d\eta' d\varphi' p_T(\eta', \varphi') \exp \left[-\frac{(\eta - \eta')^2 + (\varphi - \varphi')^2}{2\sigma^2} \right] = \max!$$

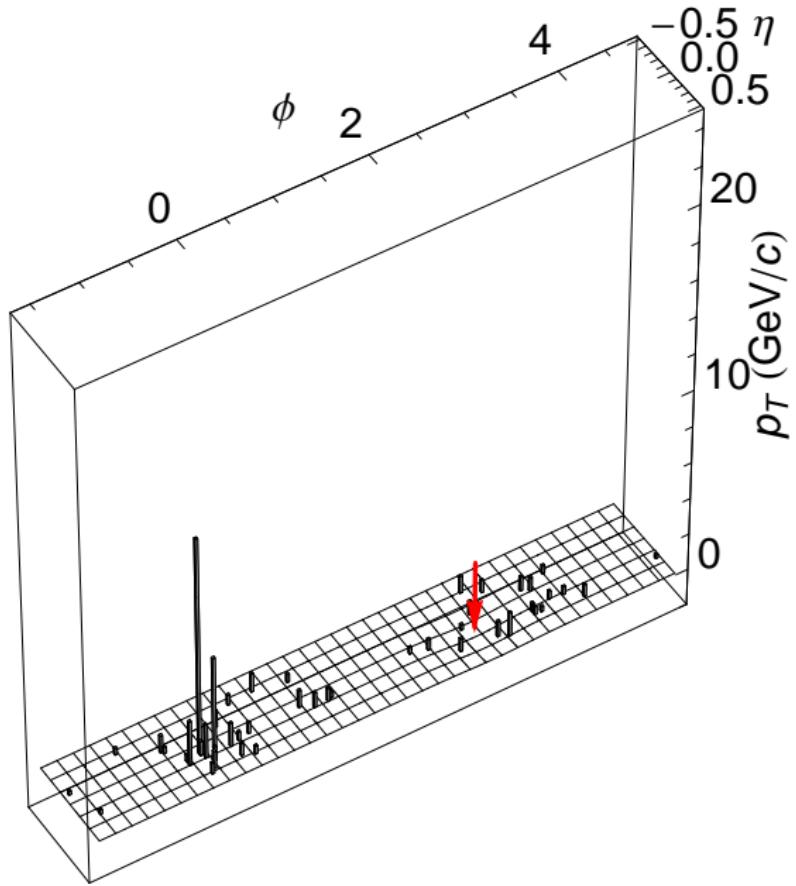


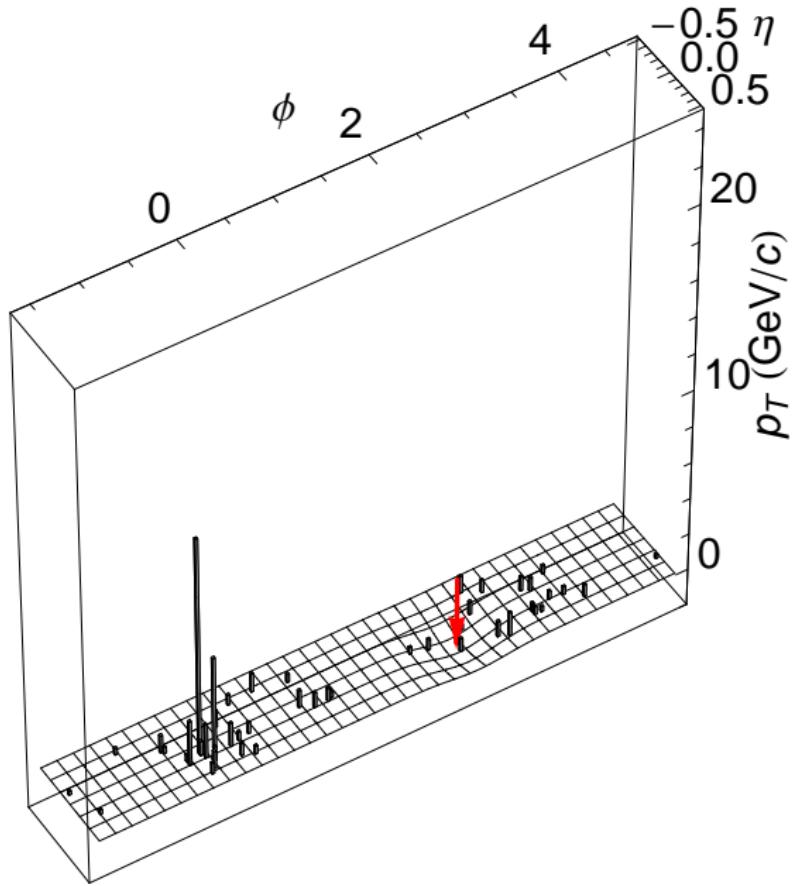
Filter

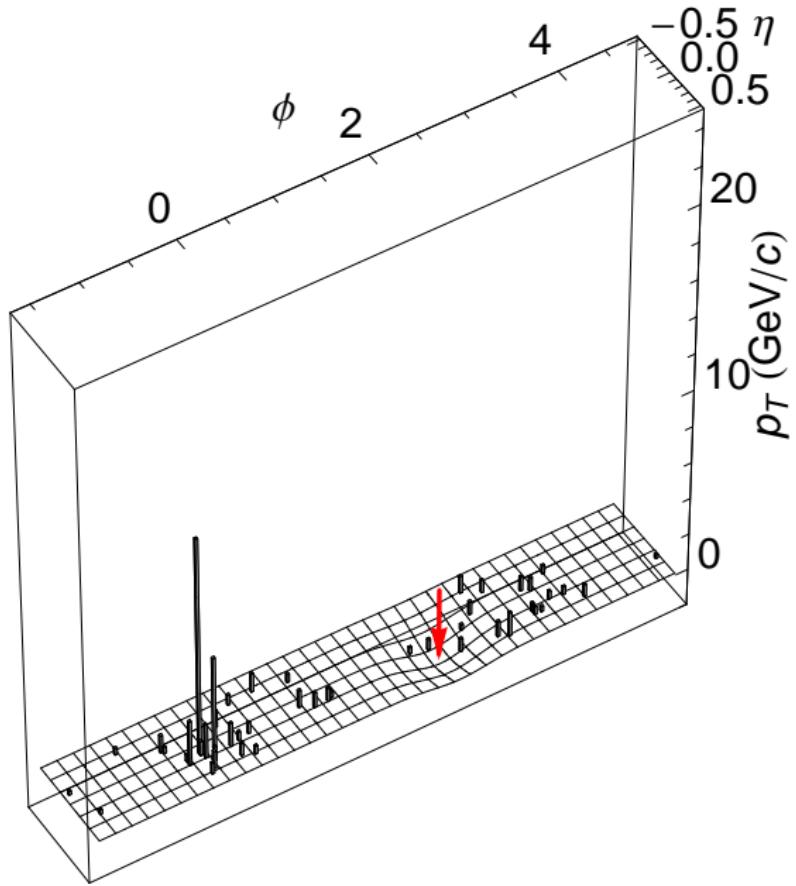
- Seedless
- Cone-like, but without infrared and collinear unsafety from hard angular cut-off
- Shape of the filter:
 - Optimizes the signal-to-background by focusing on the core of the jet
 - Stabilizes the jet axis in the presence of background
- Naturally handles isolated particles vs. collective background

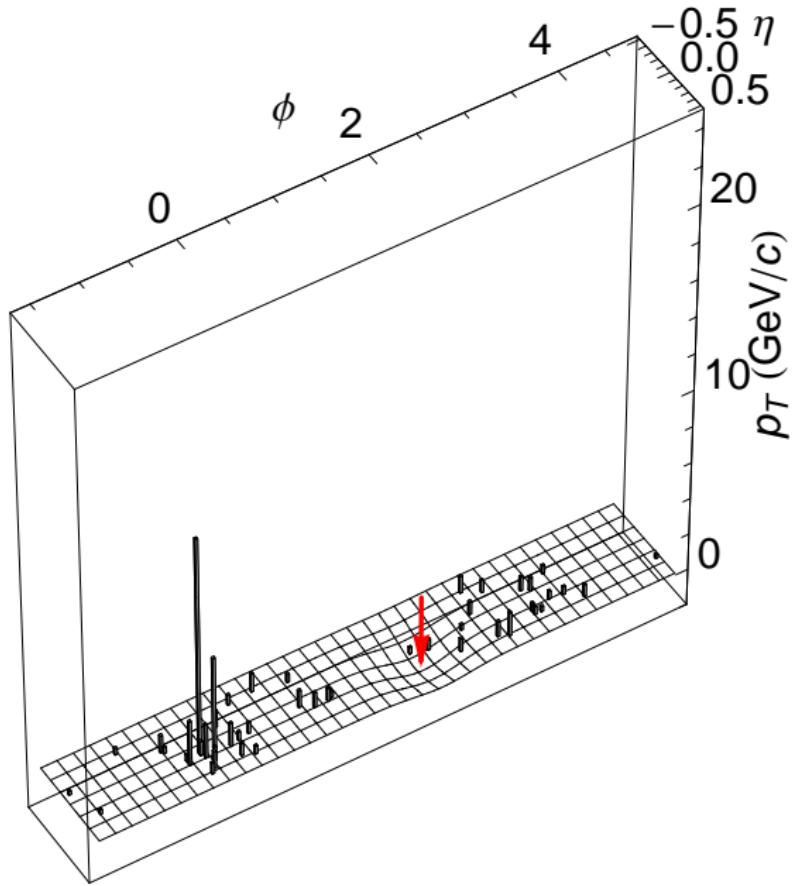


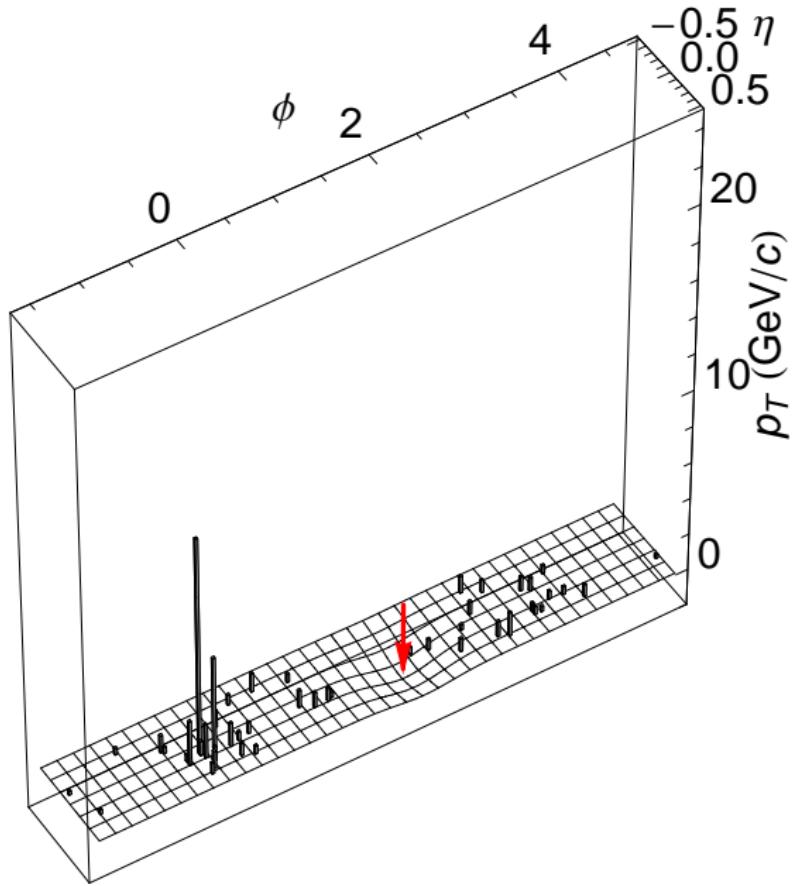


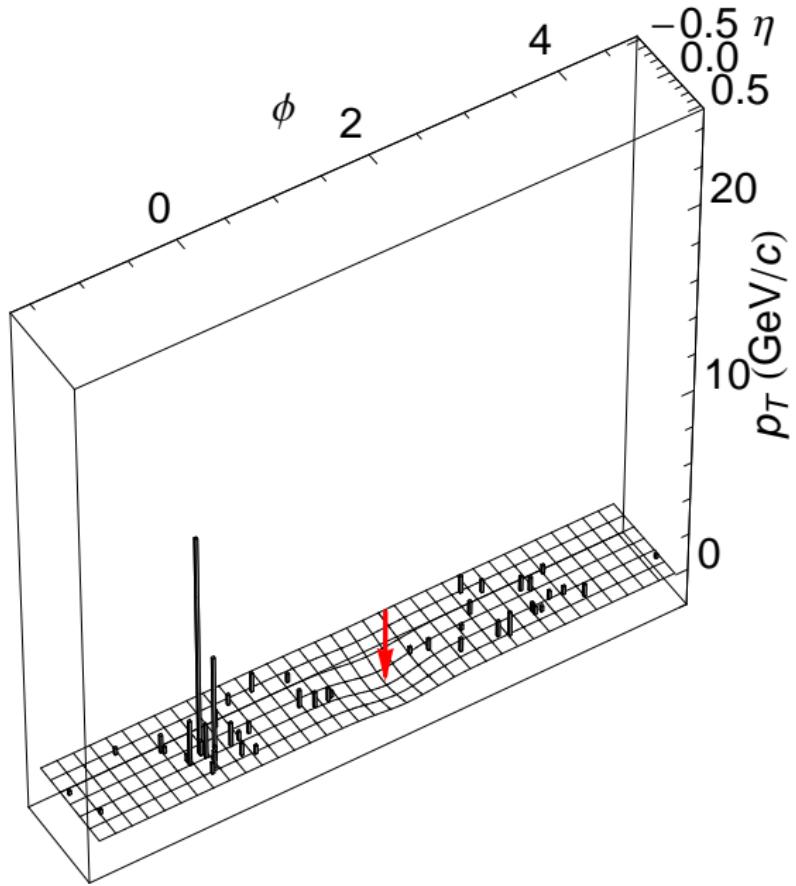


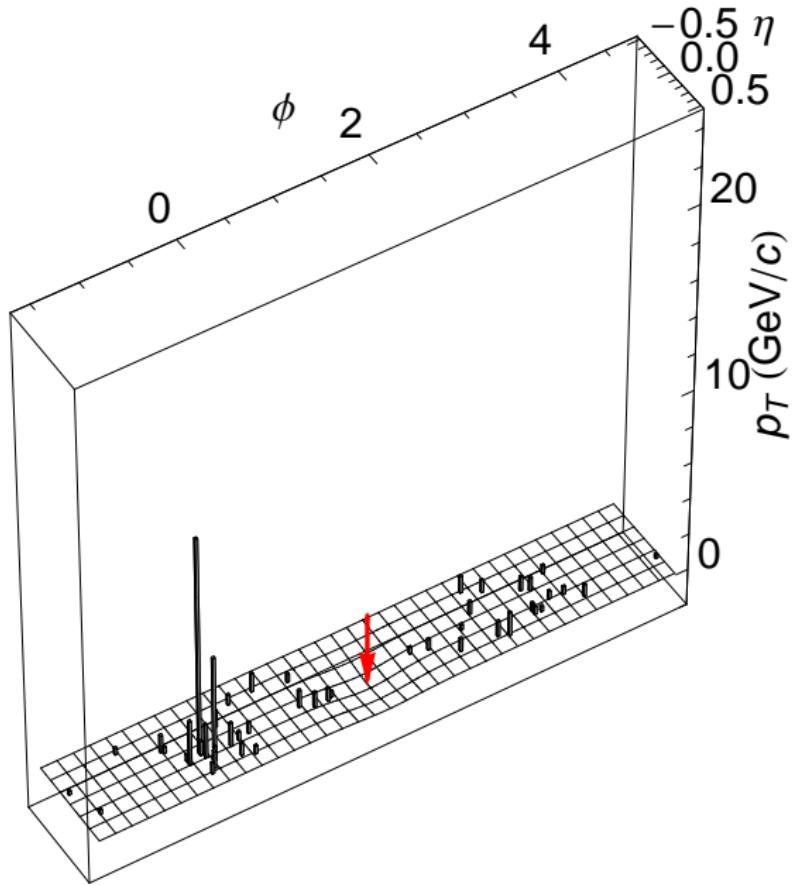


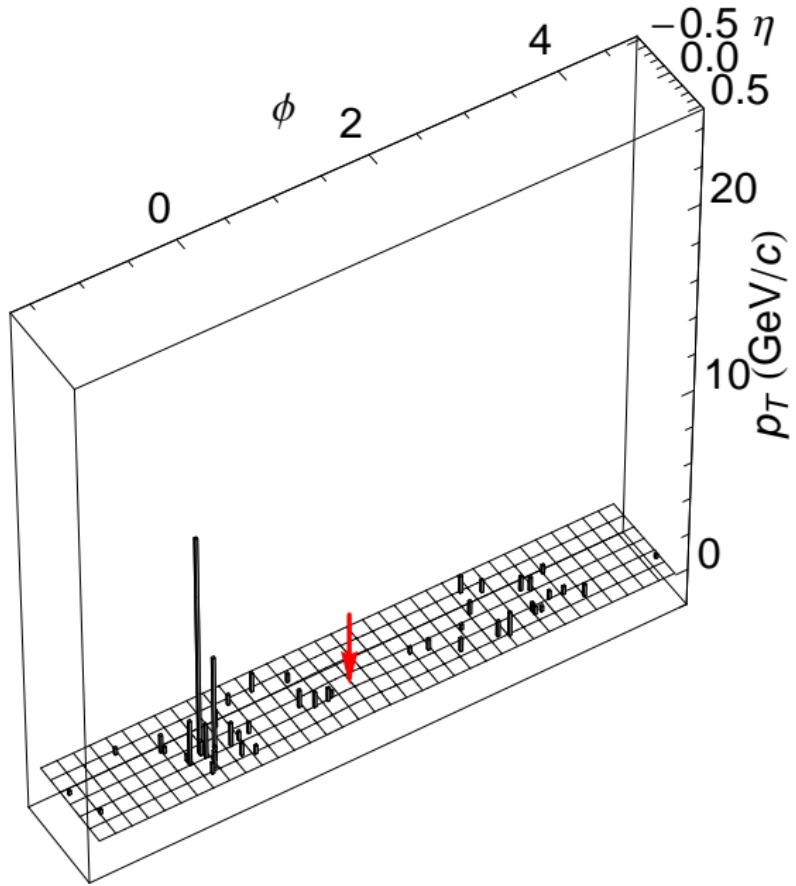


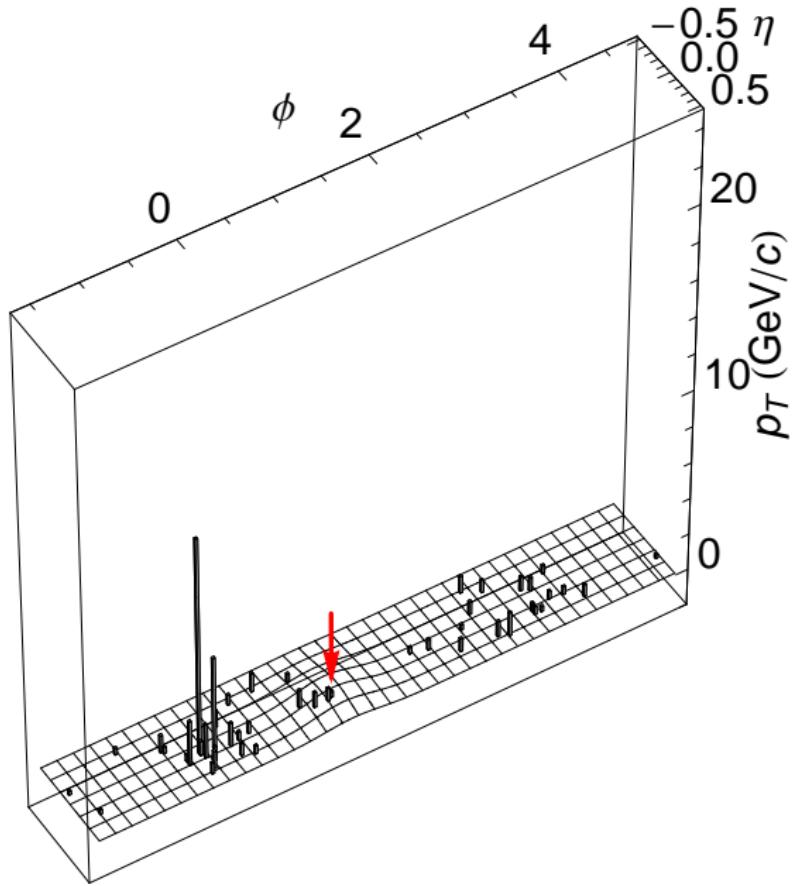


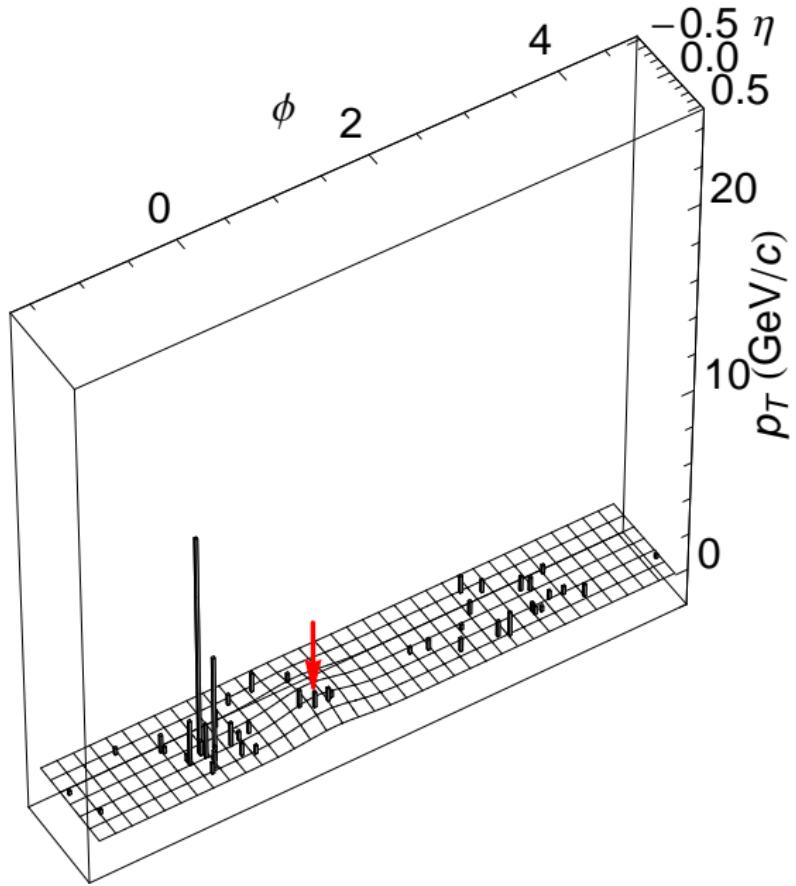


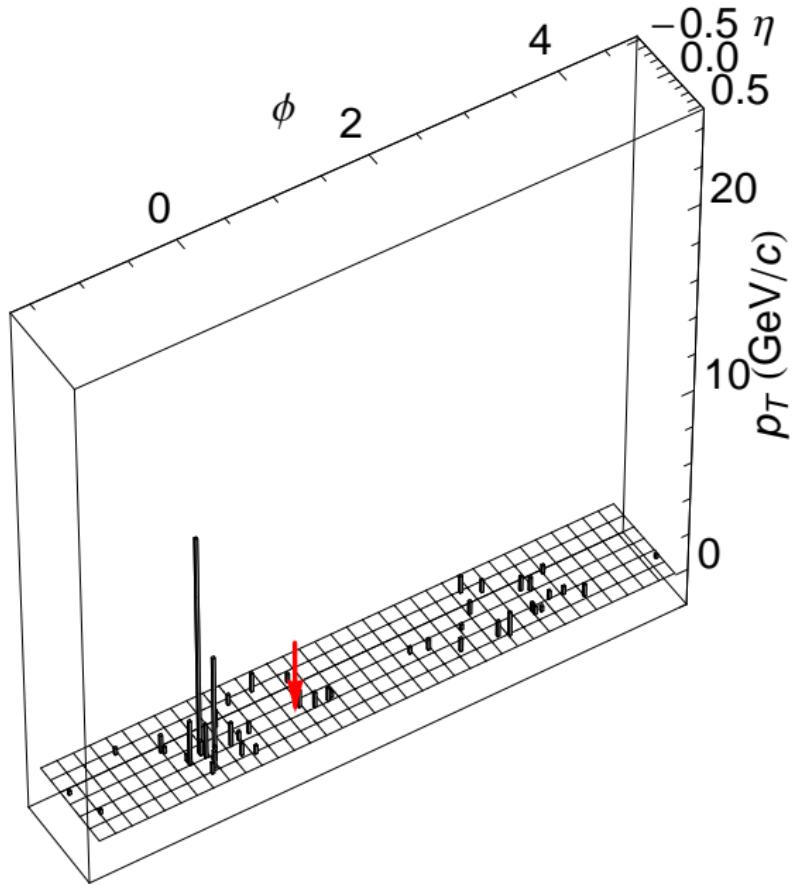


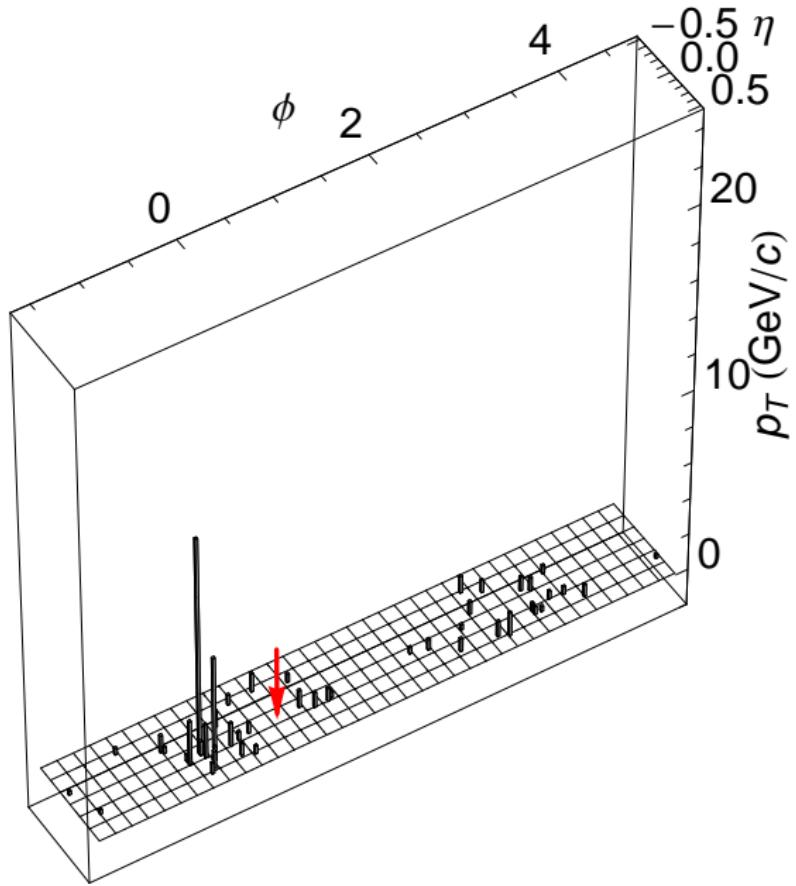


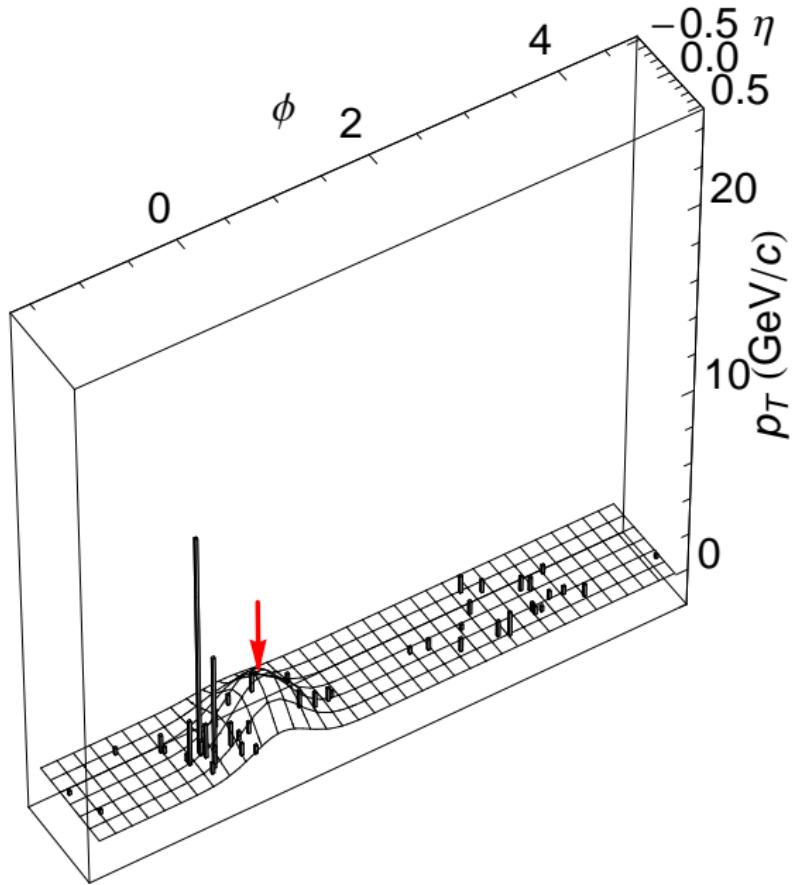


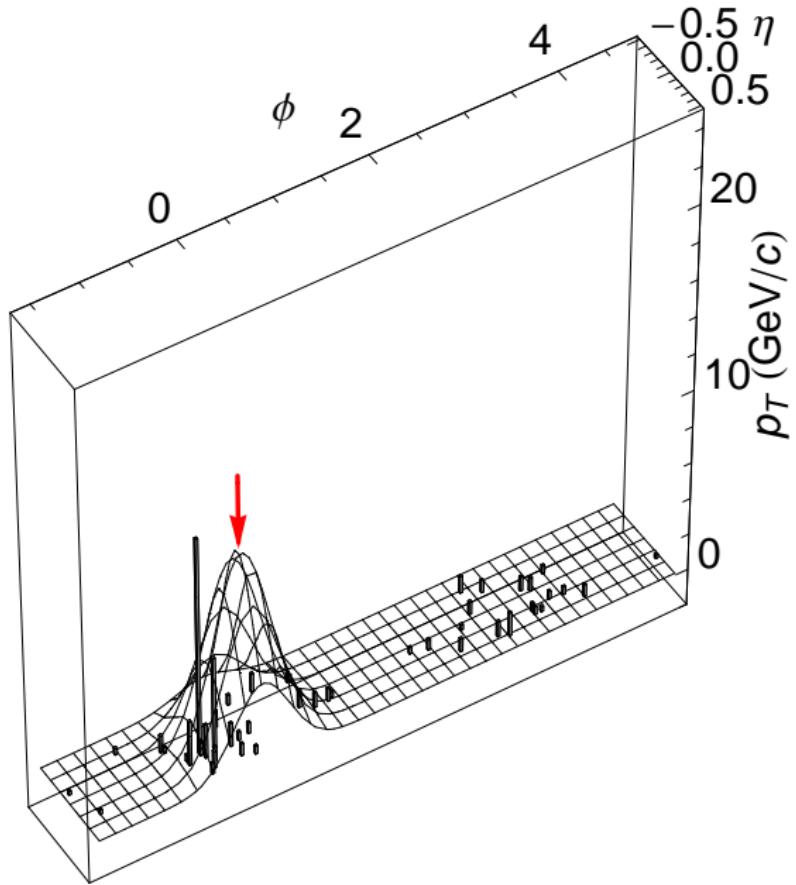


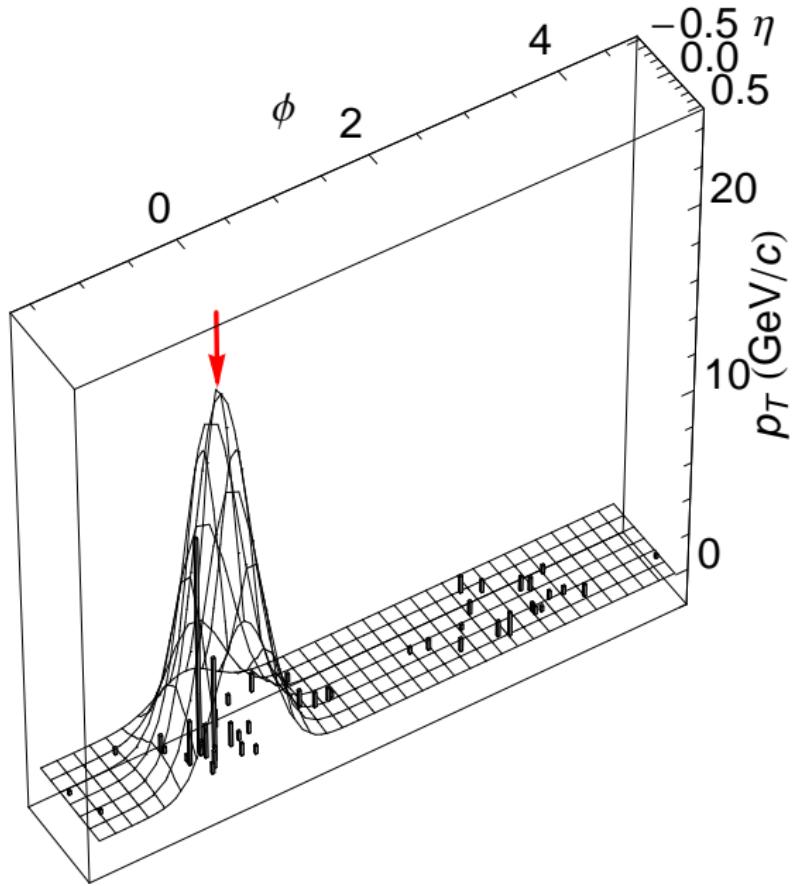


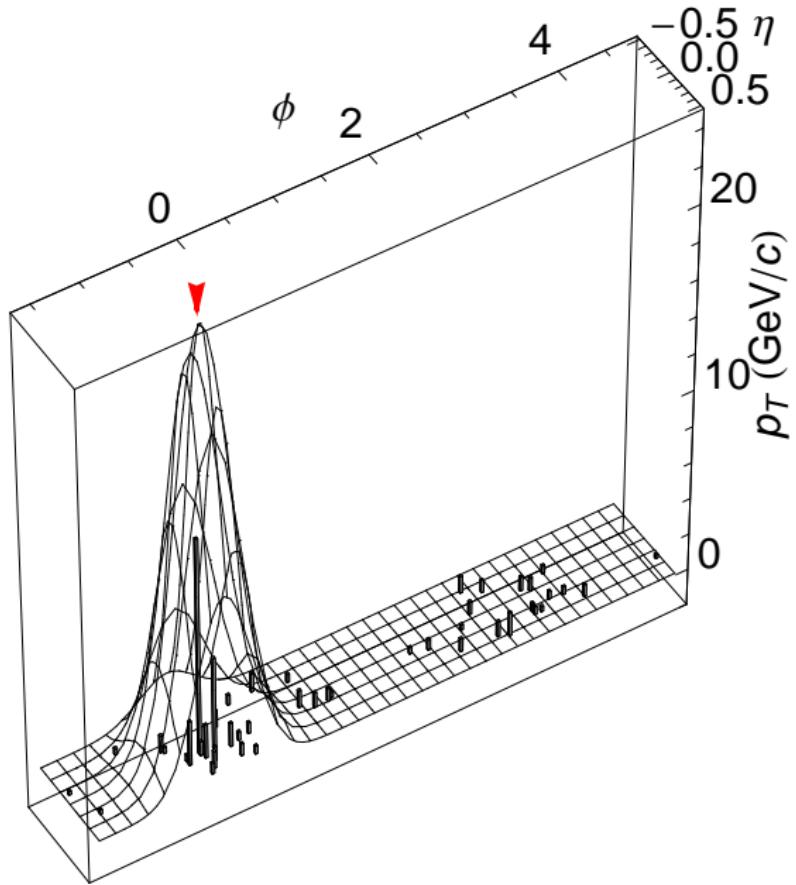


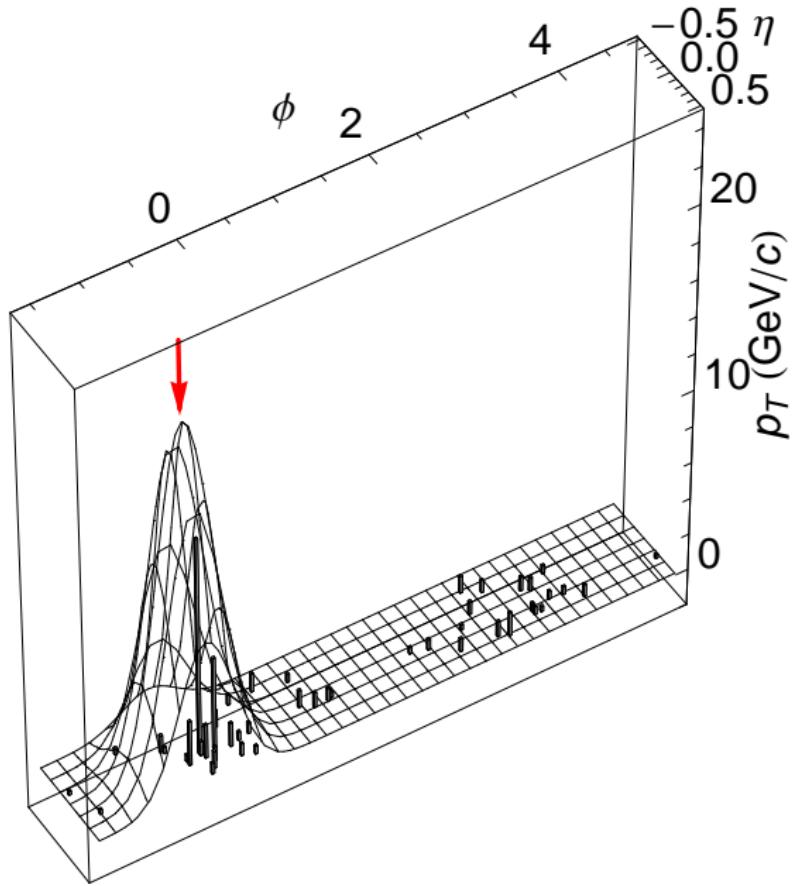


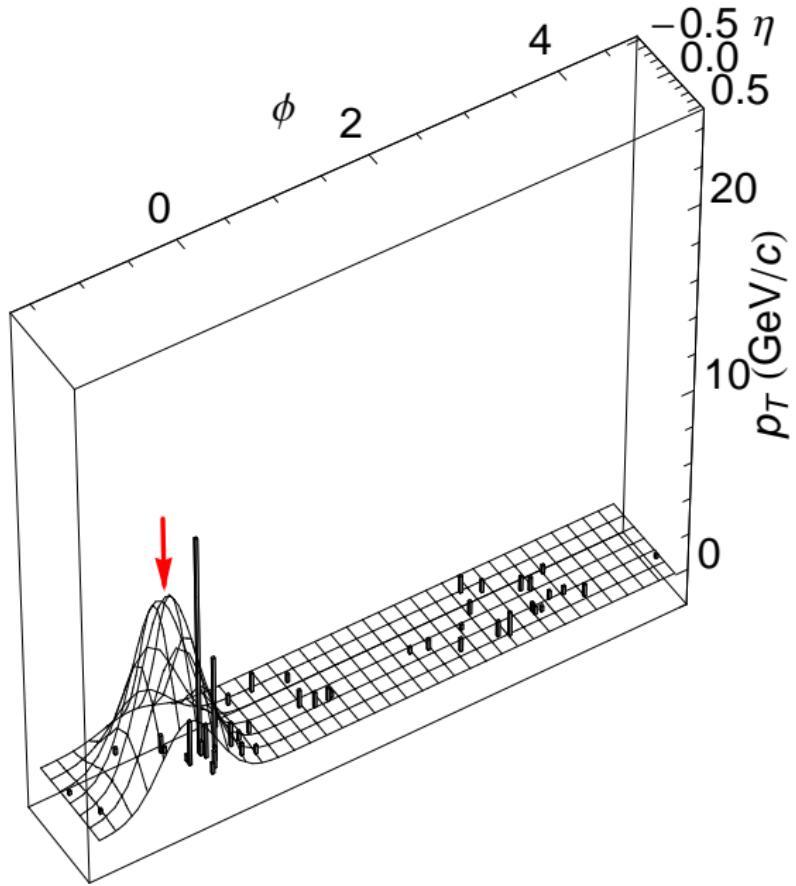


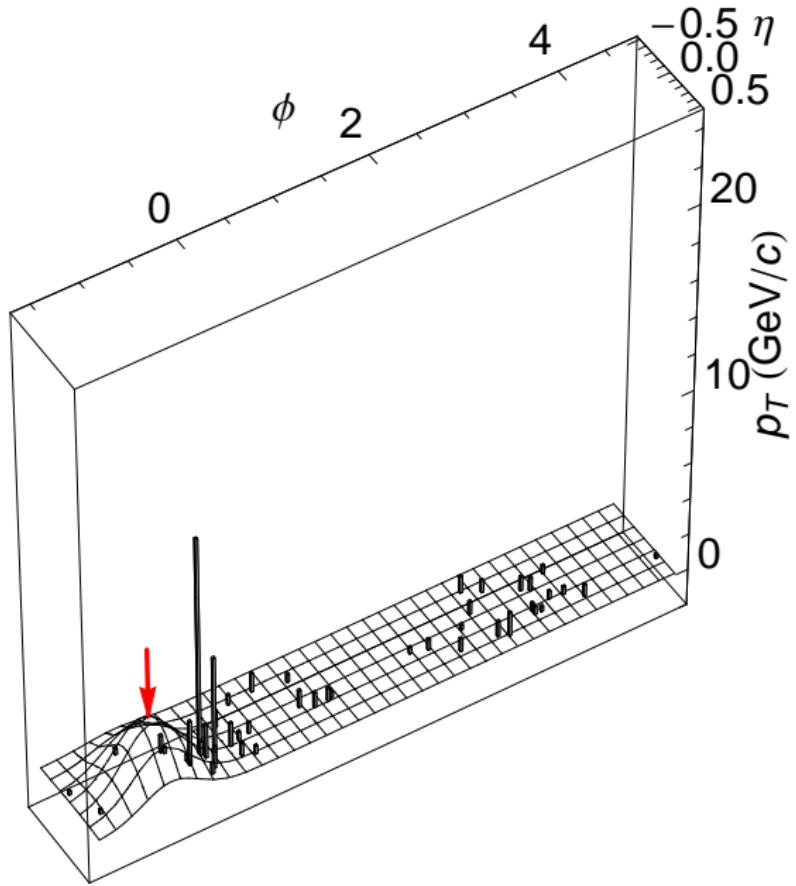


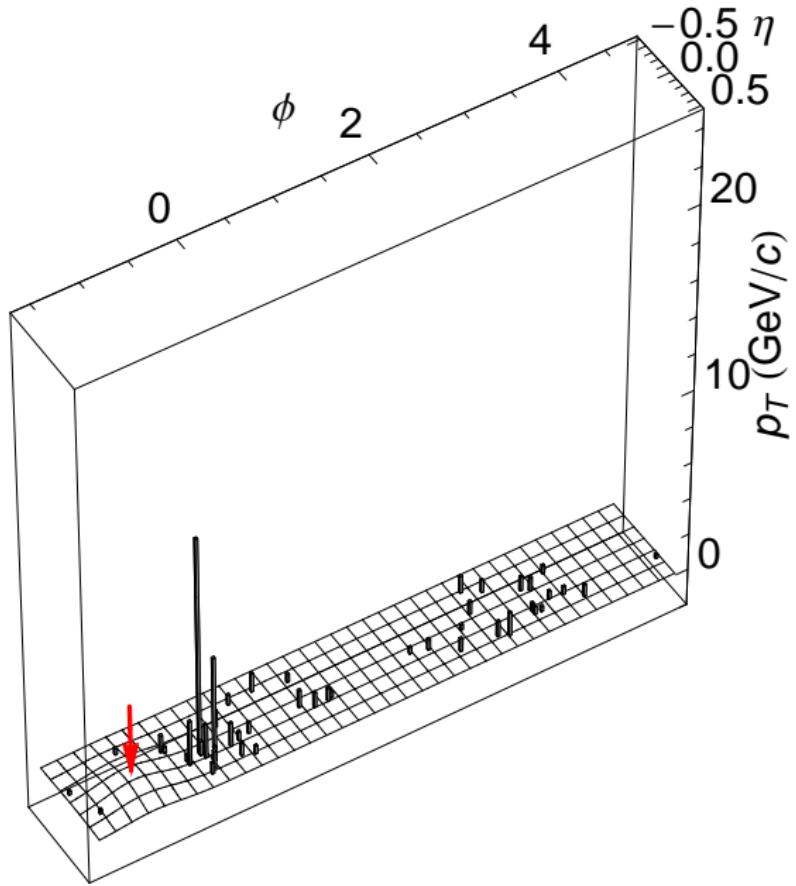


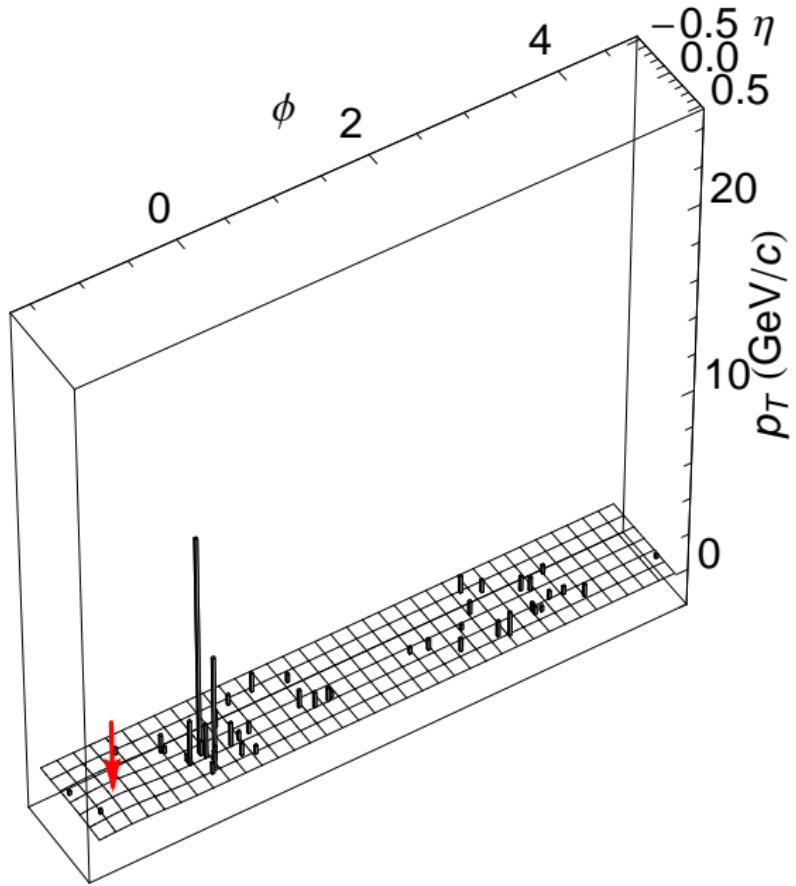


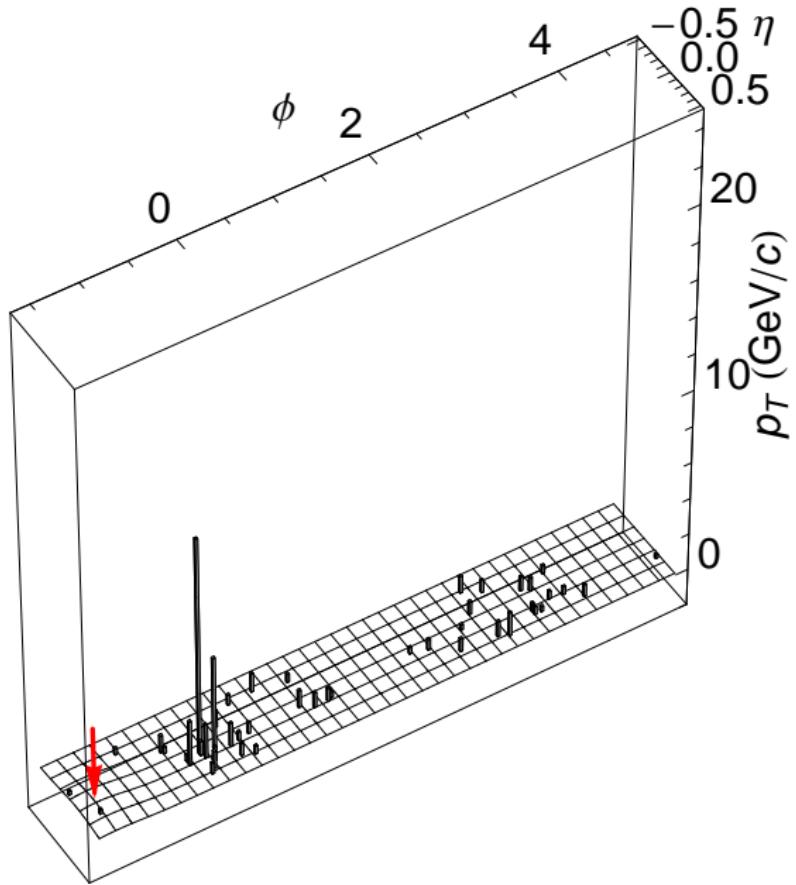




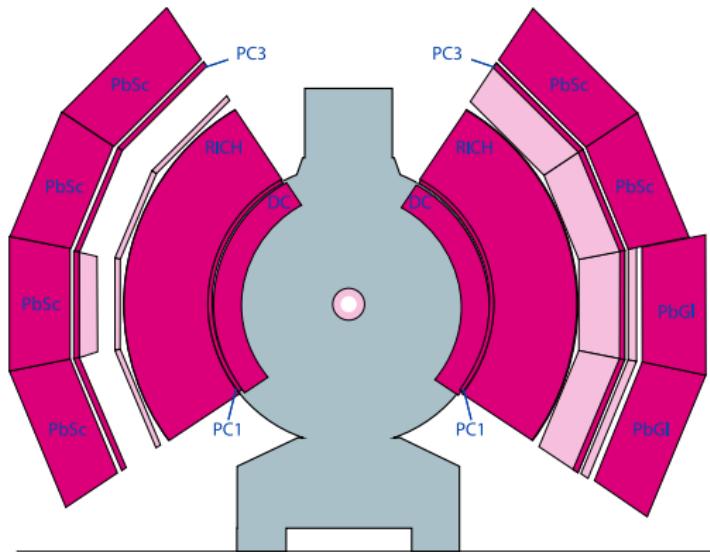






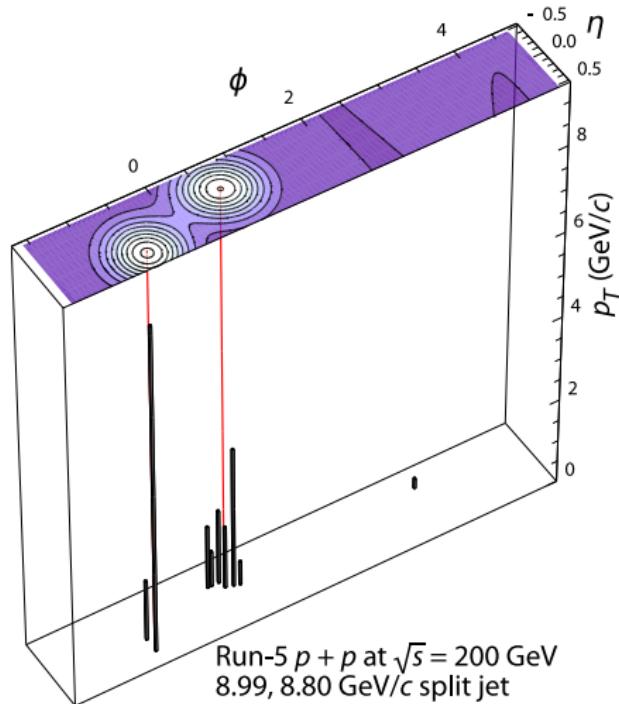
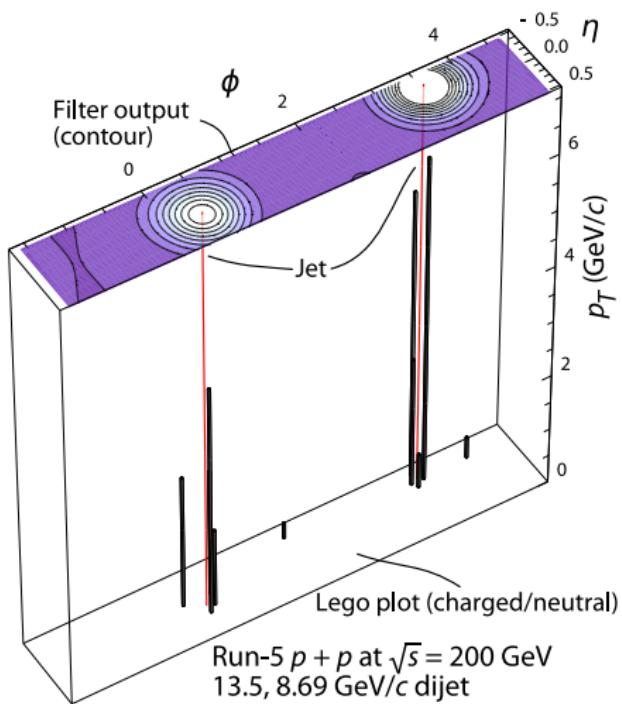


Jet reconstruction in PHENIX Run-5

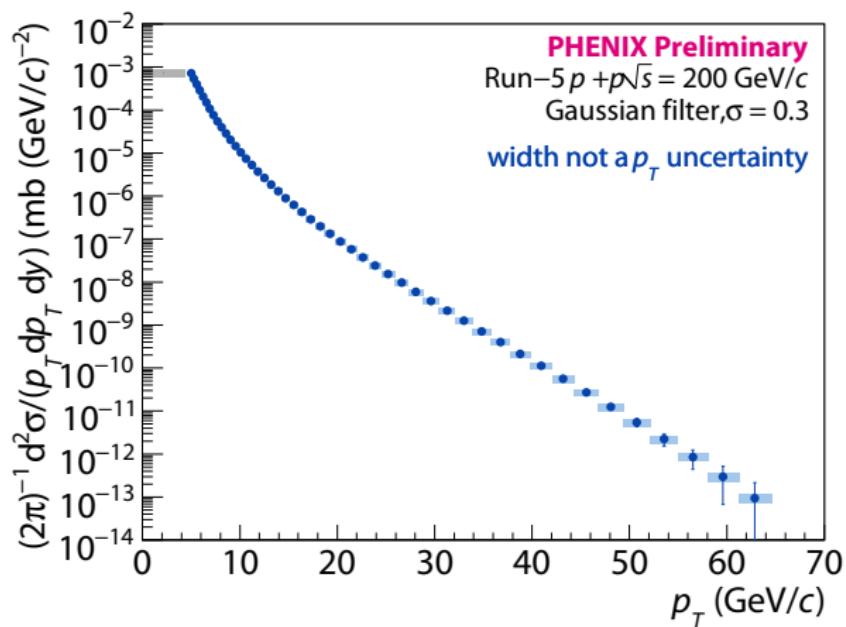


- Data set: PHENIX Run-5 $p + p$ at $\sqrt{s} = 200 \text{ GeV}$, Cu + Cu at $\sqrt{s_{NN}} = 200 \text{ GeV}$
 - Tracking detectors: Drift Chamber (DC), Pad Chambers (PC) 1/3, RICH
 - Calorimeters: Lead-Scintillator (PbSc), Lead-Glass (PbGl)
- Gaussian kernel with $\sigma = 0.3$ (mostly), $\sigma = 0.4$

Event display, $p + p$

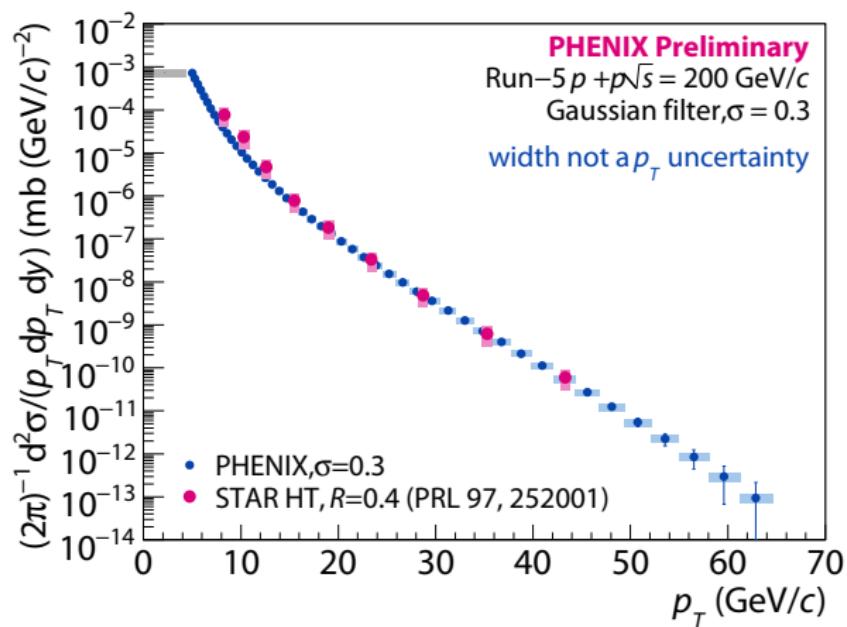


Run-5 $p + p$ spectrum



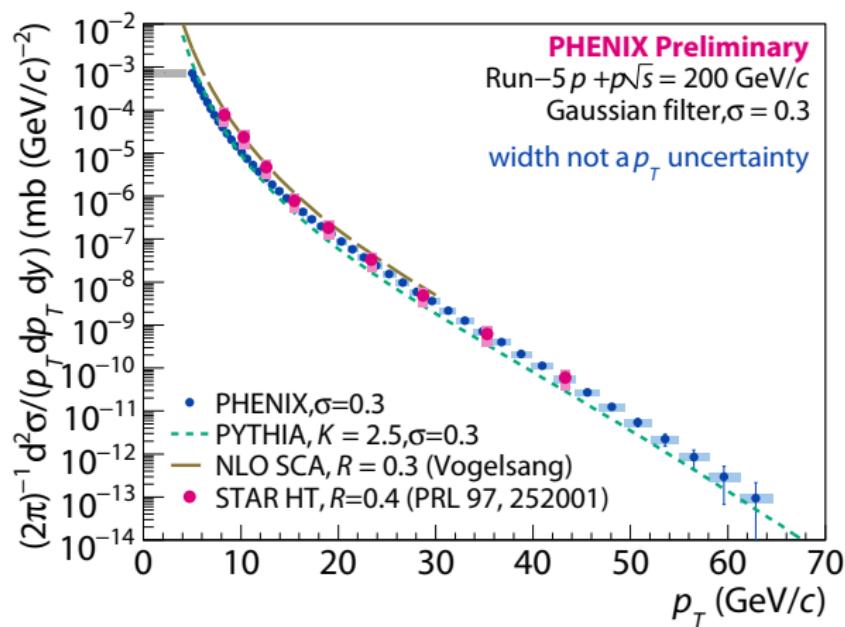
- $\int \mathcal{L} = 2.2 \text{ pb}^{-1}$
- Regularized SVD unfolding (GURU, Höcker & Kartvelishvili, NIM A 372, 469)

Run-5 $p + p$ spectrum



- Cross section consistent with STAR HT, but $x_{\max} \approx 0.6$
- $\sigma = 0.3$ not the same as $R = 0.4$ midpoint cone, but apparently close

Run-5 $p + p$ spectrum



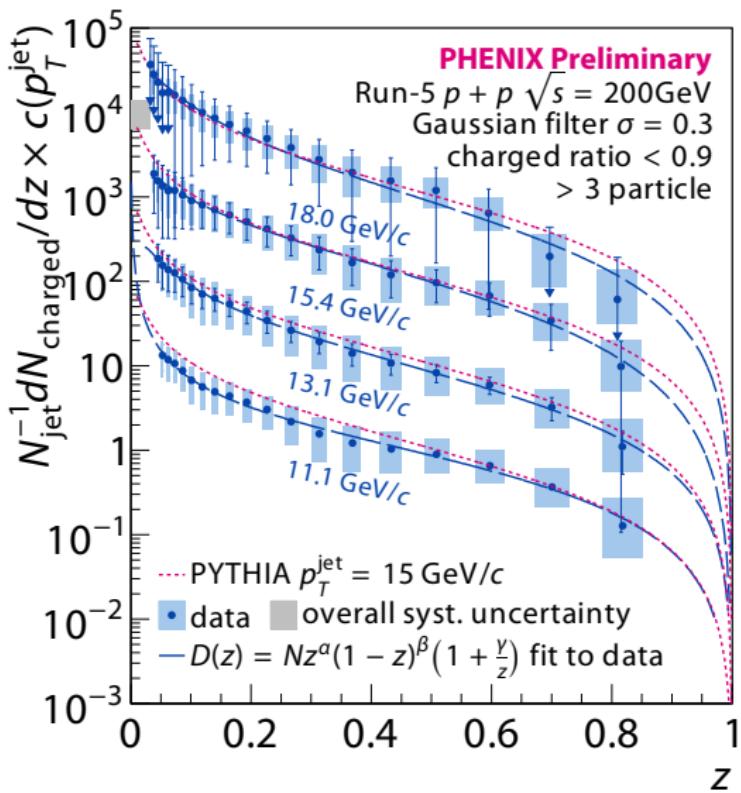
- PYTHIA leading order K and NLO SCA also applies to oranges
- NLO calculation for larger p_T range and using filter is needed

Notes about fragmentation functions

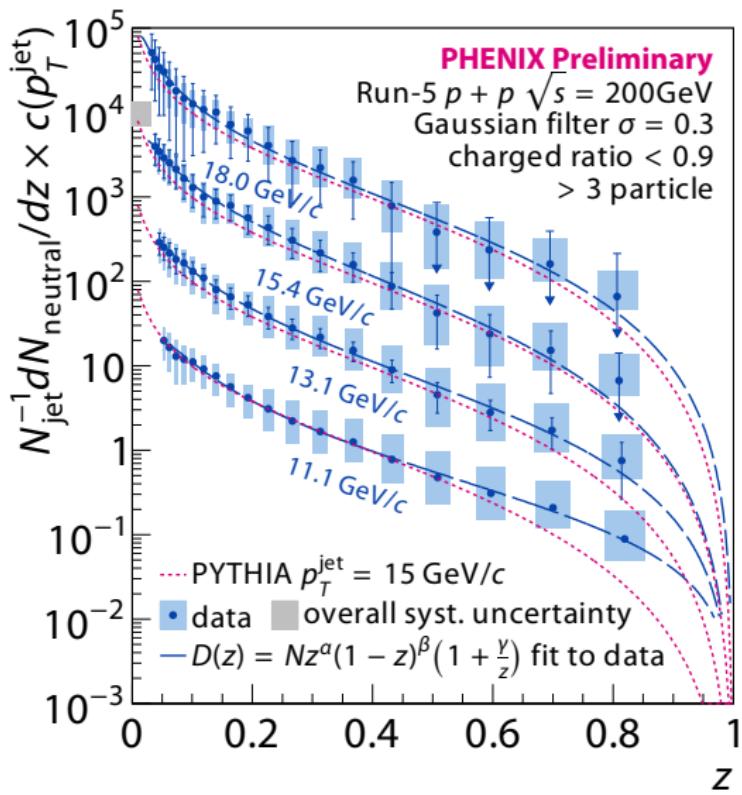
- $z = p_{\parallel}^{\text{particle}} / p^{\text{jet}}$
 - ⇒ p^{jet} must be the true jet energy to perform “apple-to-apple” division
 - ⇒ Otherwise z is shifted
- 2D unfolding needed to simultaneously unfold $(p_{\parallel}^{\text{particle}}, p^{\text{jet}})$
 - ⇒ We developed a n -D generalization to GURU
 - ⇒ First time 2D regularized SVD unfolding is applied in HEP/NP
- Data shown uses Run-5 $p + p$ minimum bias (triggered data is in the works)
- Direct comparison to (perfect detector) PYTHIA at $p_T^{\text{jet}} = 15 \text{ GeV}/c$
- Particle species:
 - Non-ID charged tracks (rejecting e^{\pm})
 - Neutral clusters (electromagnetic)
- Single particle resolution not yet unfolded (very small effect)

Run-5 $p + p$ fragmentation function

- Charged particles (with e^\pm rejection)
- $z = p_{\parallel}^{\text{particle}} / p_T^{\text{jet}}$
- $c(\cdot) = 10^i, i = 0, 1, \dots$
- Jet cut bias uncorrected, but fully quoted in the systematic uncertainty
- $z_{\max} \approx 0.81$

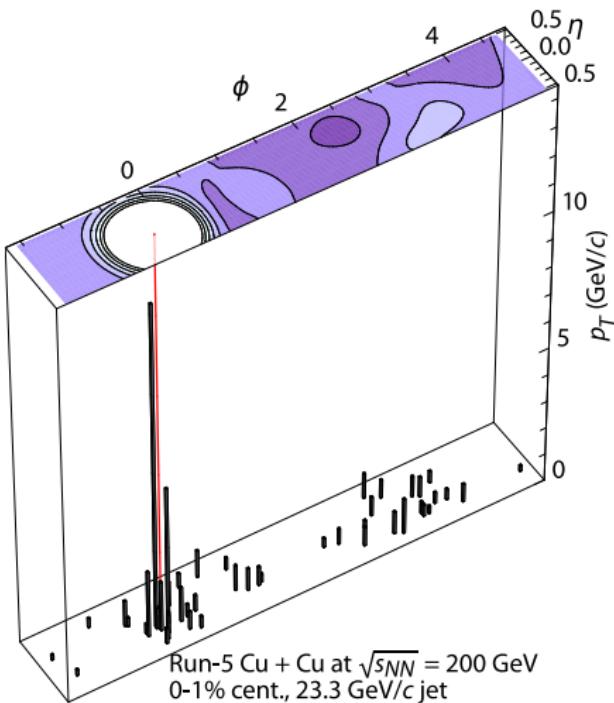
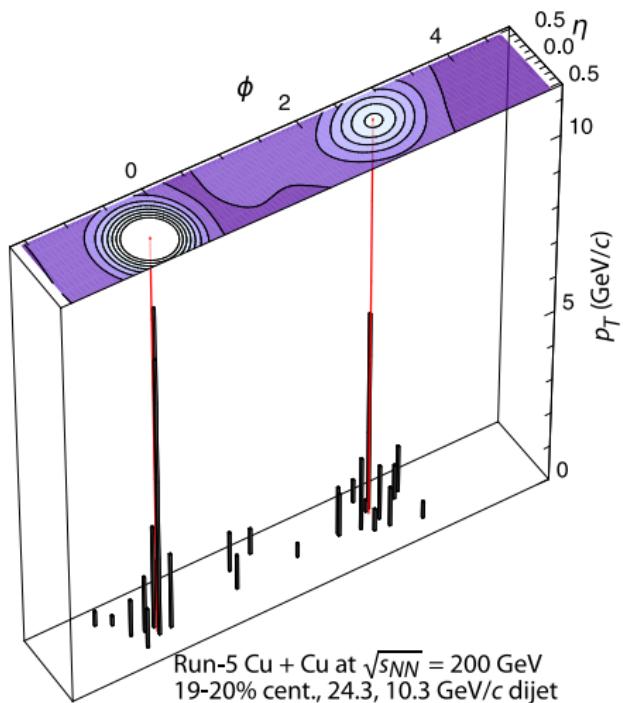


Run-5 $p + p$ fragmentation function



- Neutral particles (electromagnetic)
- $z = p_{\parallel}^{\text{particle}}/p_T^{\text{jet}}$
- $c(\cdot) = 10^i, i = 0, 1, \dots$
- Jet cut bias uncorrected, but fully quoted in the systematic uncertainty
- $Z_{\text{max}} \approx 0.81$

Event display, Cu + Cu



Jet reconstruction in RHIC heavy ion: fake jets

- Large $dN/d\eta$, small jet σ_{pp} (vs. LHC):

⇒ Cu + Cu central jet yield at 10 GeV/c,

$$\frac{1}{2\pi} \frac{1}{N_{\text{evt}}} \frac{dN}{p_T dp_T dy} \approx 10^{-6} (\text{GeV}/c)^{-2} :$$

⇒ Several approach are proposed/may be suitable for jet reconstruction:

- 1 Reconstruct only very high p_T jets
- 2 Apply a large p_T cut on fragments
- 3 Statistically subtract the background
- 4 Direct rejection of fake jets

- Approach (4) is preferred by PHENIX:

- Low and controllable biases
- Residual systematic errors easier to estimate/correct

Gaussian fake rejection

- Cut on the overall shape of the jet
- Inspired by the principle of Gaussian filter
- Strategy:

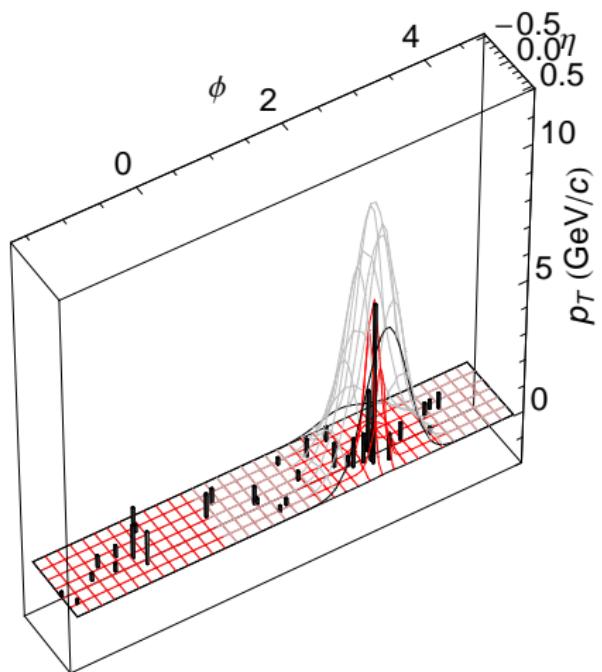
1 Sum p_T^2 inside a Gaussian kernel to obtain a discriminant:

$$g_{\sigma_{\text{dis}}}(\eta, \varphi) = \sum_{i \in \text{fragment}} p_{T,i}^2 \exp \left[-\frac{(\eta_i - \eta)^2 + (\varphi_i - \varphi)^2}{2\sigma_{\text{dis}}^2} \right],$$

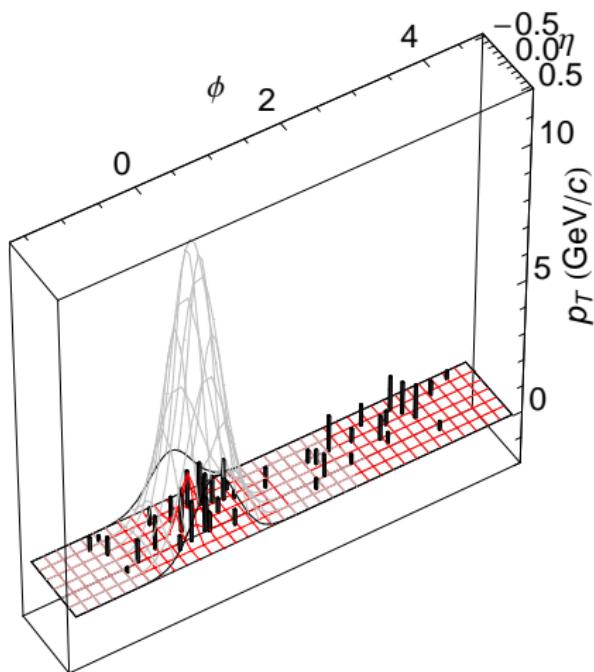
- 2 Gaussian kernel $\sigma_{\text{dis}} \approx 0.1$
3 (Technical detail: allow adaption for jets with very close maxima, obtain an updated $g'_{\sigma_{\text{dis}}}$)

- Cut on $g'_{0.1} = \text{weighted } p_T^2\text{-sum}$
- In central Au + Au HIJING simulation proves to be more effective than $\sigma/\sqrt{\langle A \rangle}$ (Cacciari & Salam, Phys. Lett. B **659**, 119, 2008) and Σj_T (Grau *et al.*, arXiv:0810.1219, 2008)

Principle of fake rejection

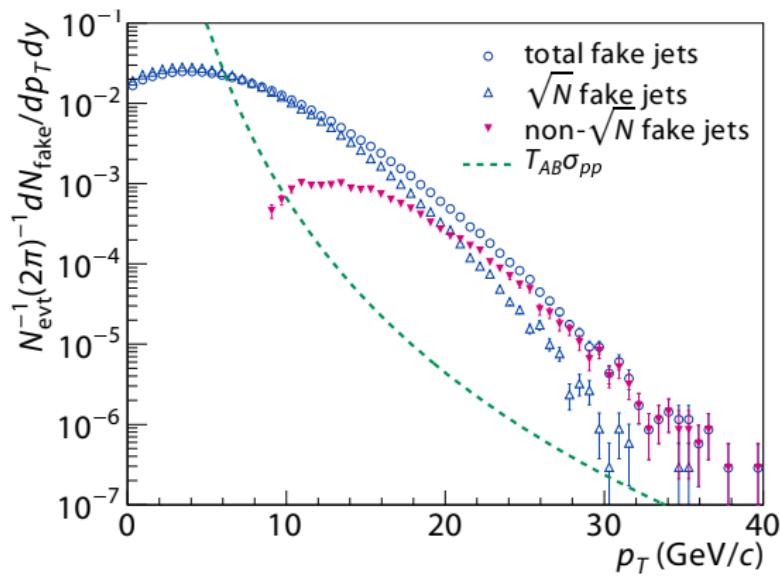


9.6 GeV/c jet passing fake rejection



Rejected 10.8 GeV/c background fluctuation

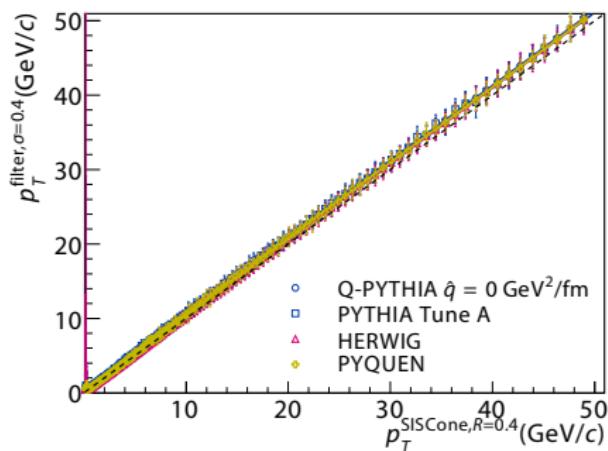
QCD background: \sqrt{N} ?



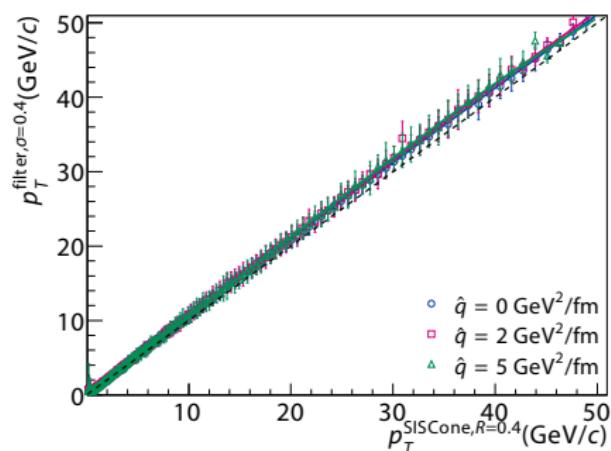
- $\sqrt{s_{NN}} = 200 \text{ GeV Au + Au HIJING}$
- Most of the high p_T portion not \sqrt{N} fluctuation, yield well above $T_{AB}\sigma_{pp}$
- HIJING background may be overly pessimistic, but demonstrates:
⇒ **\sqrt{N} a highly dangerous assumption**

Energy scale in heavy ion environment

- $\sigma = 0.4$ Gaussian filter vs. $R = 0.4$ SIScone:



All at default settings

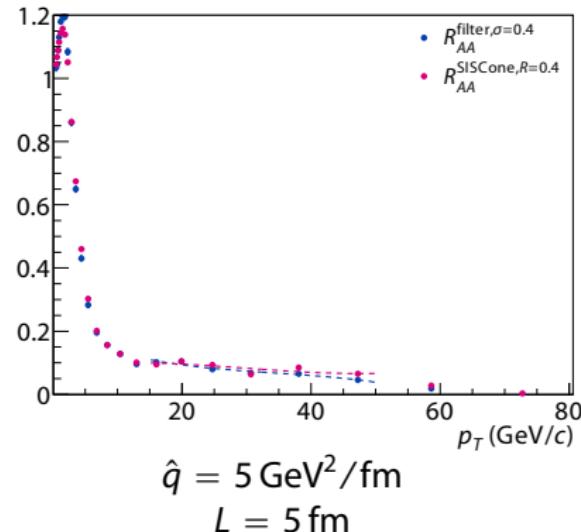
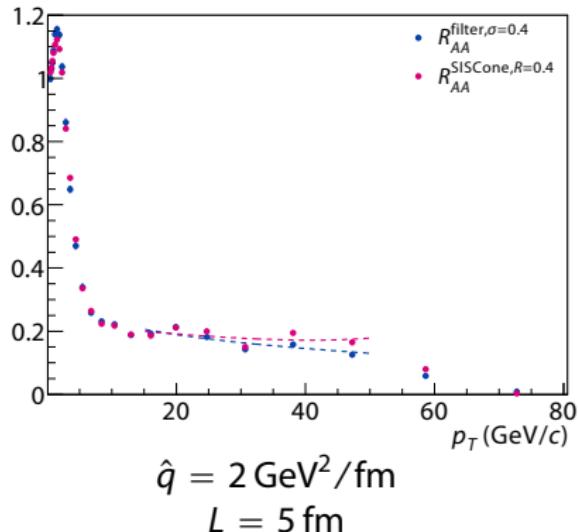


Q-PYTHIA with $L = 5 \text{ fm}$

- Algorithmic “preference” of vacuum or quenched jets is a myth
- Jet algorithms respond extremely similar to quenching, residual differences are far below current detector uncertainties
- Behavior in PYQUEN observed in Grau *et al.*, arXiv:0810.1219 (2008)

Is the R_{AA} strongly dependent on the jet algorithm?

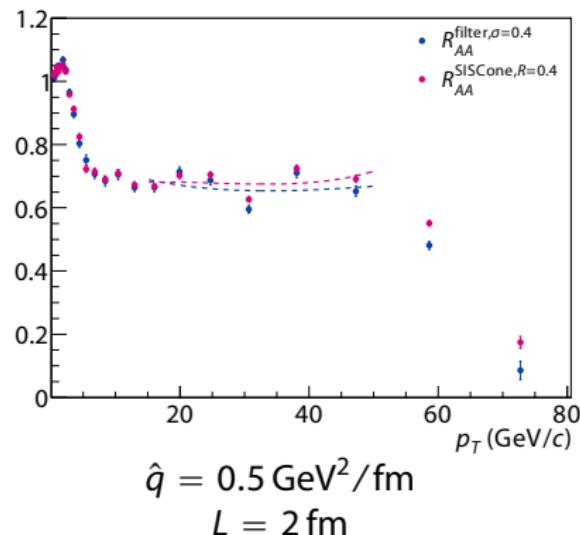
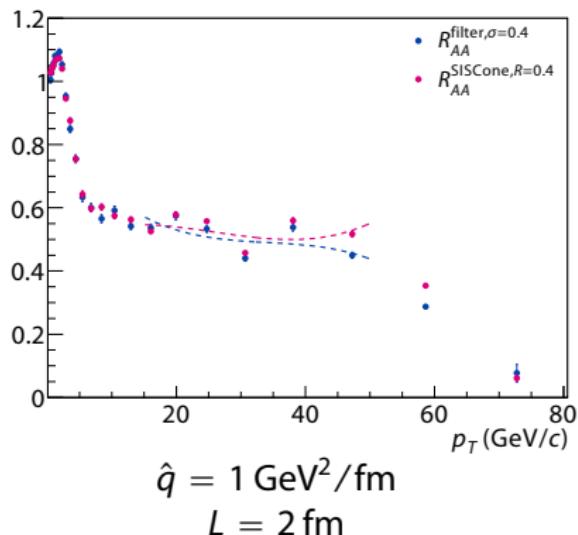
- $\sigma = 0.4$ Gaussian filter vs. $R = 0.4$ SIScone, Q-PYTHIA strong quenching:



- True algorithm dependent differences in Q-PYTHIA R_{AA} prediction tiny, $\Delta R_{AA} \approx 0.05$, and only noticeable beyond $30 \text{ GeV}/c$
⇒ **Inaccessible by current detector systematics**

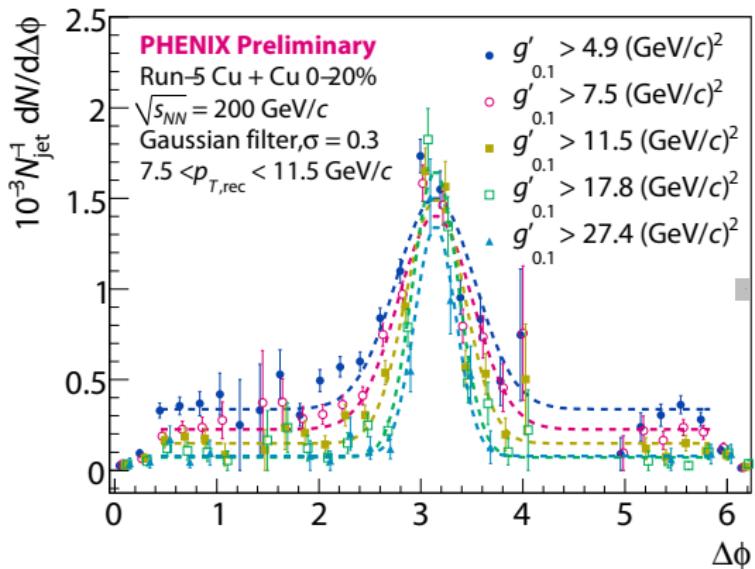
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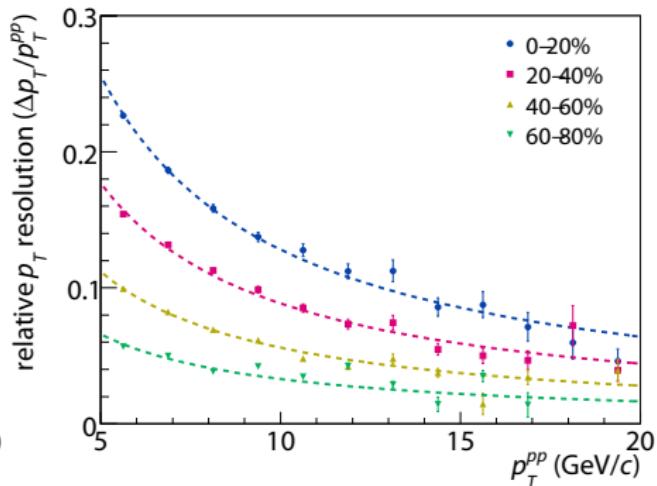
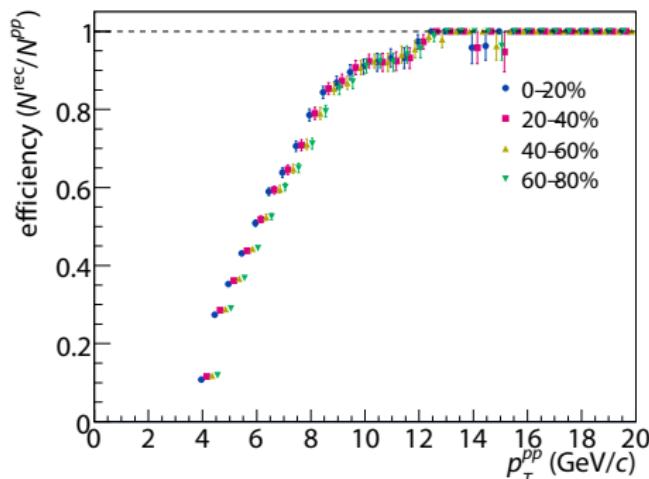
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Fake rejection in Cu + Cu



- Pedestal $\approx 0.3 \times 10^{-3}$ translates into $\frac{1}{2\pi} \frac{1}{N_{\text{evt}}} \frac{dN}{p_T dp_T dy} \approx 10^{-5} (\text{GeV}/c)^{-2}$, substantial contamination for 7.5 GeV/c
- 17.8 (GeV/c)² used as standard fake rejection cut level:
⇒ < 10% contamination at 7.5 GeV/c

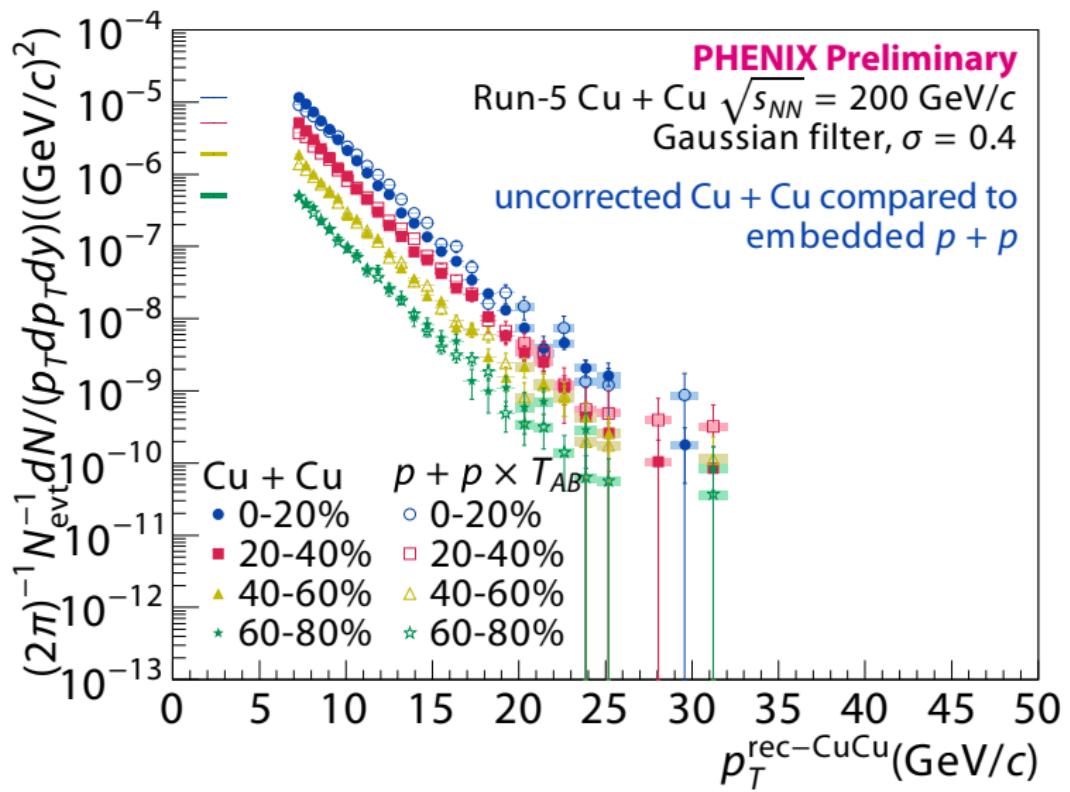
$p + p$ embedding in Cu + Cu: performance



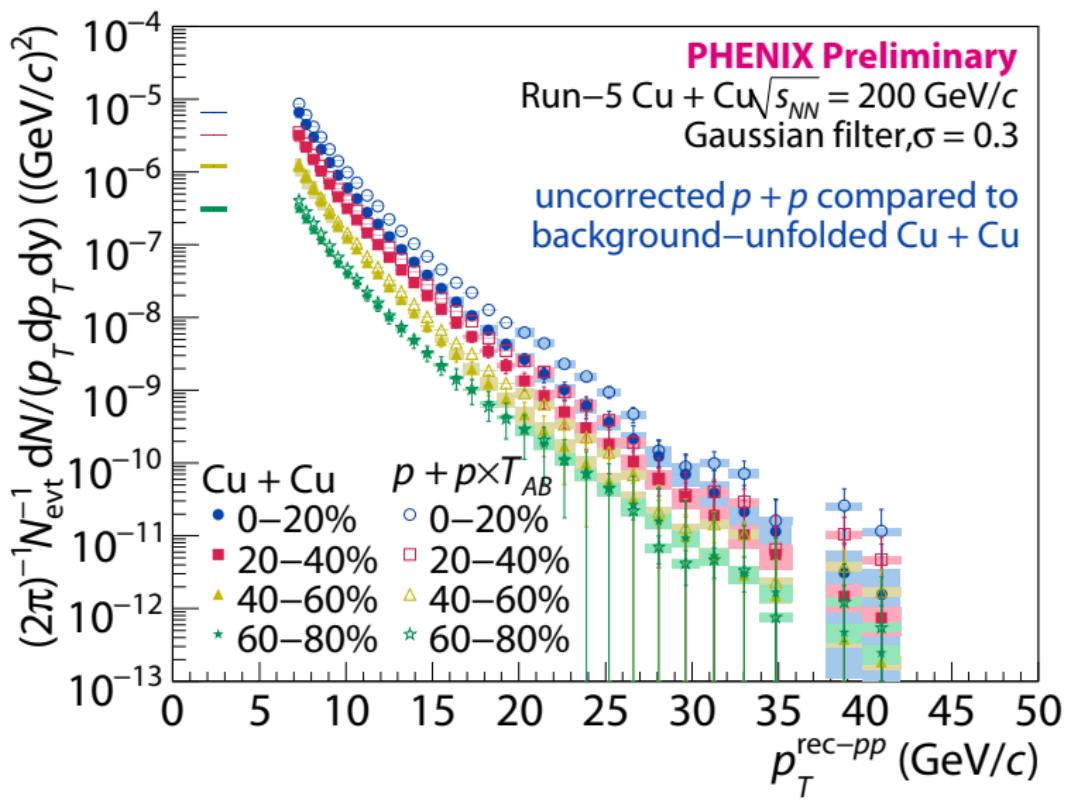
Several desirable properties for heavy ion jet reconstruction:

- Fast saturation to unitary efficiency
- **Negligible centrality dependence of jet reconstruction efficiency**
 - Efficiency includes the fake rejection

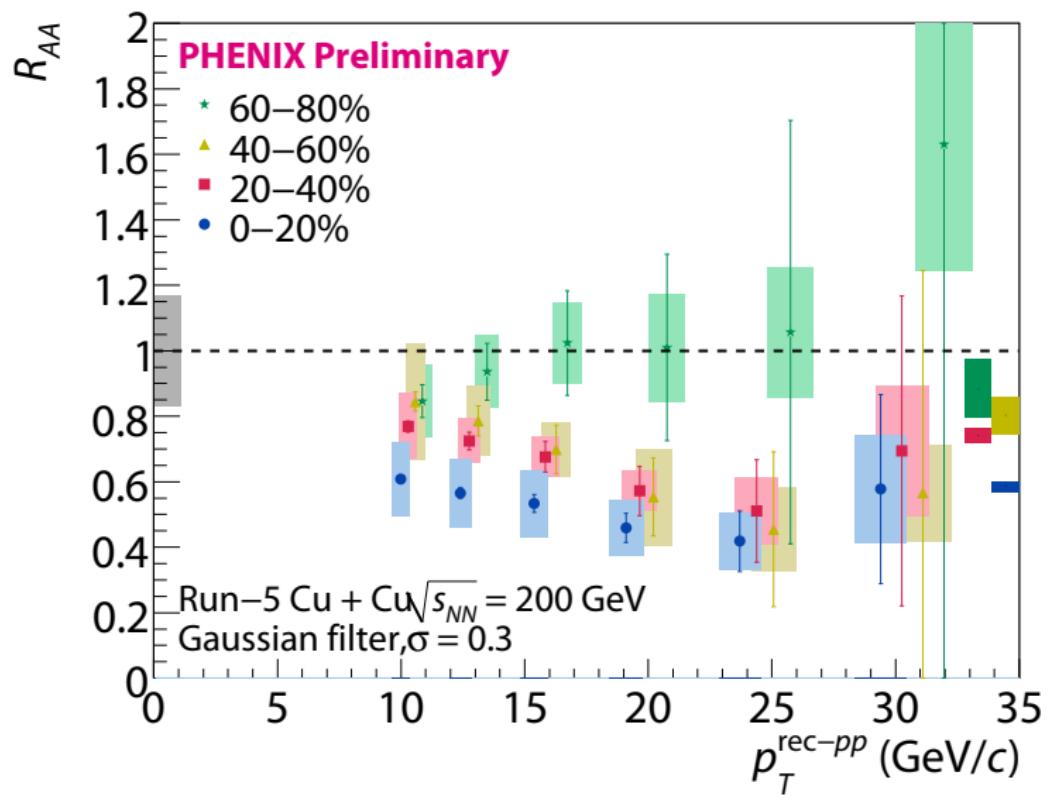
Run-5 Cu + Cu spectra, $\sigma = 0.4$ (embedding)



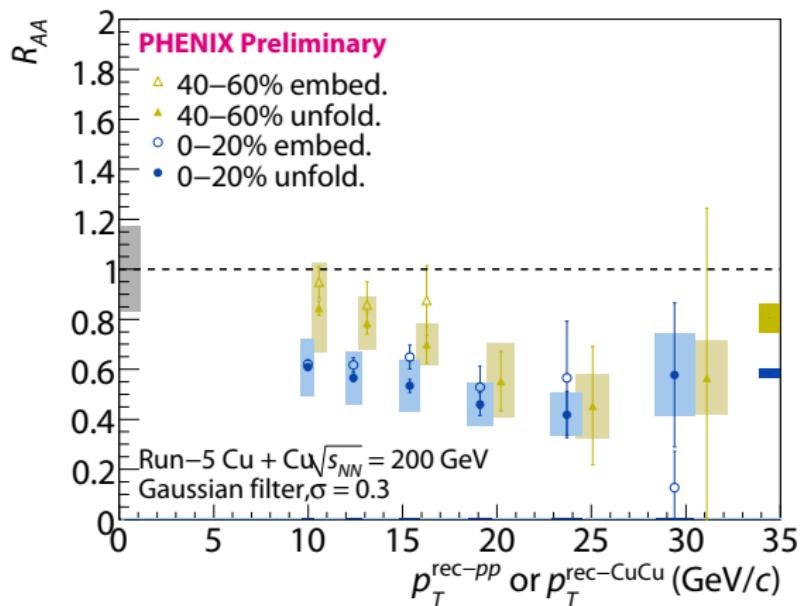
Run-5 Cu + Cu spectra, $\sigma = 0.3$ (unfolding)



Run-5 Cu + Cu R_{AA} , $\sigma = 0.3$

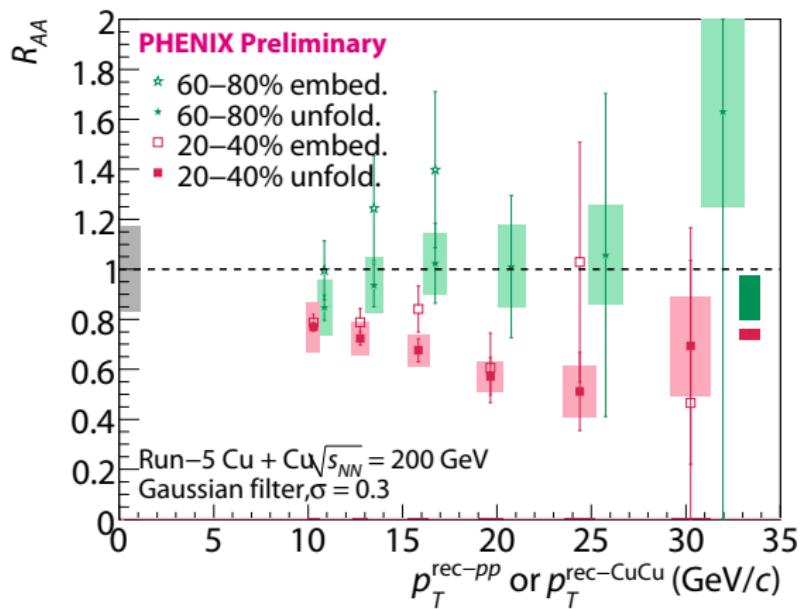


Run-5 Cu + Cu R_{AA} , $\sigma = 0.3$ compared to embedding



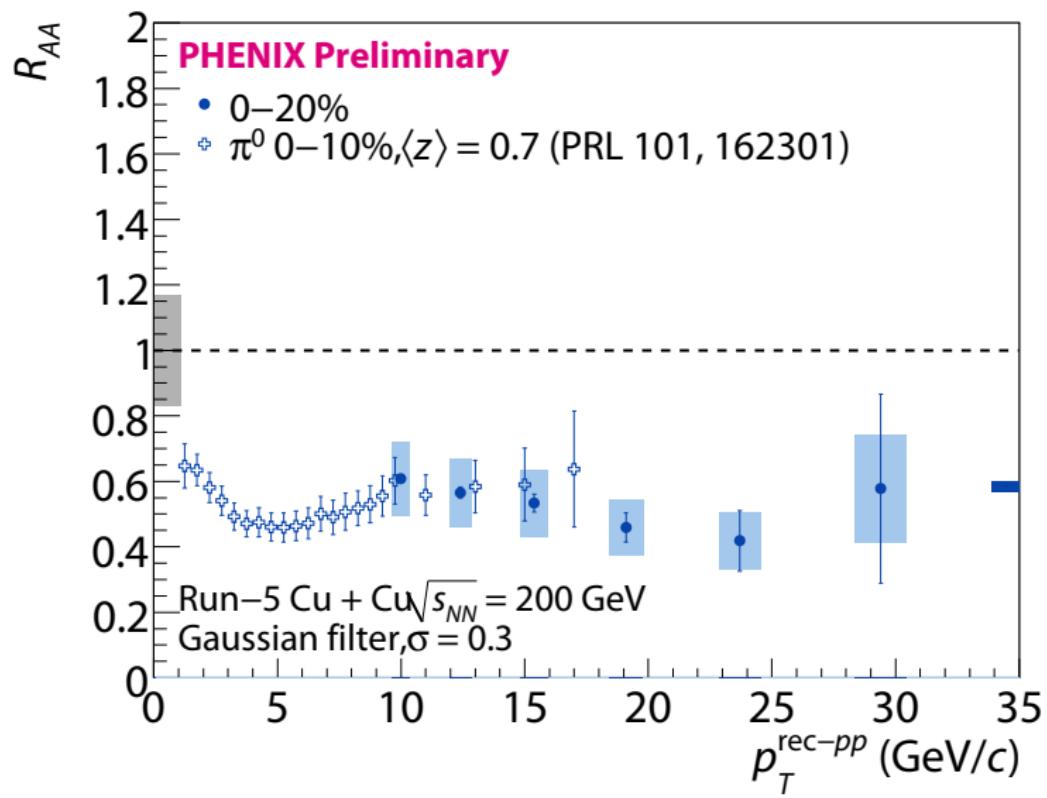
- Unfolded: uncorrected $p + p$ compared to background-unfolded Cu + Cu
- Embedded: uncorrected Cu + Cu compared to embedded $p + p$
- Mismatching energy scale, but R_{AA} is roughly flat

Run-5 Cu + Cu R_{AA} , $\sigma = 0.3$ compared to embedding

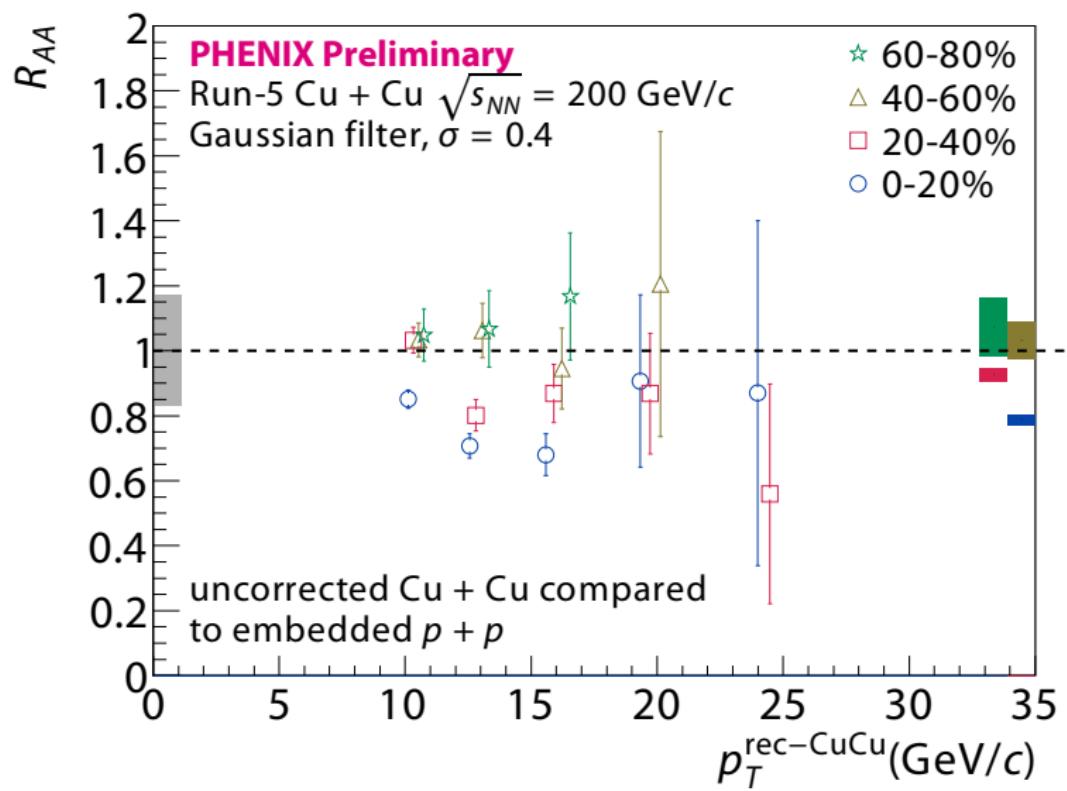


- Unfolded: uncorrected $p + p$ compared to background-unfolded Cu + Cu
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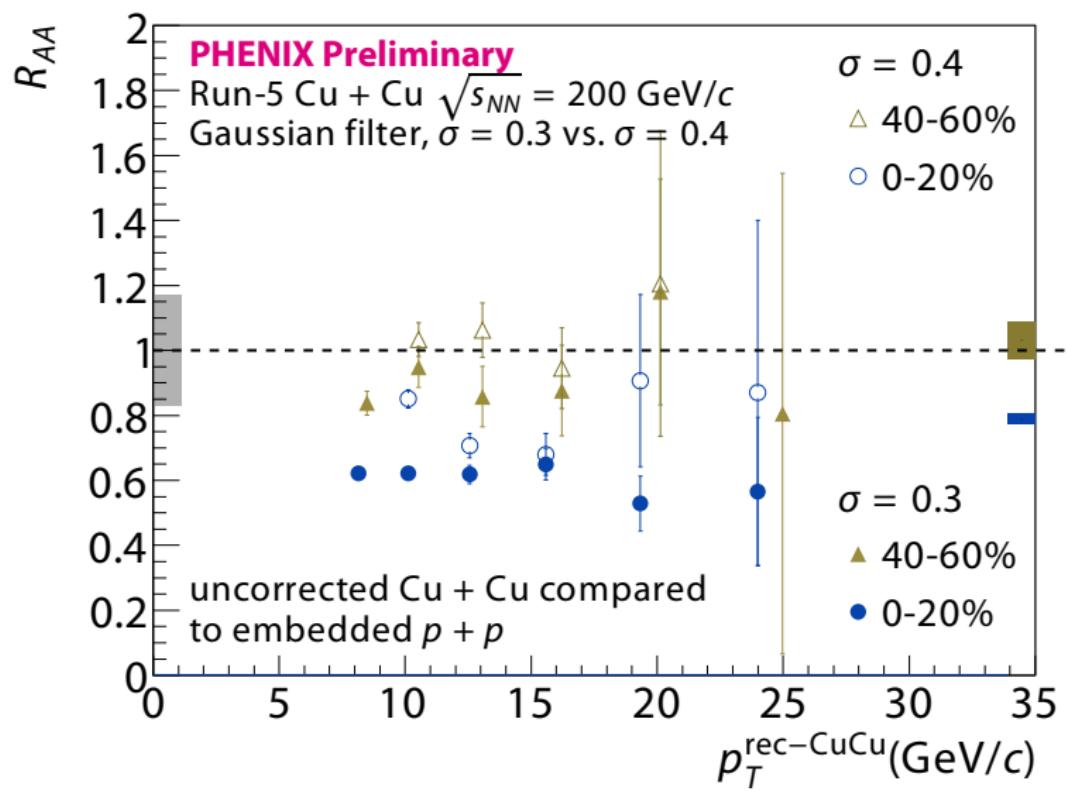
Run-5 Cu + Cu R_{AA} , $\sigma = 0.3$ compared to π^0



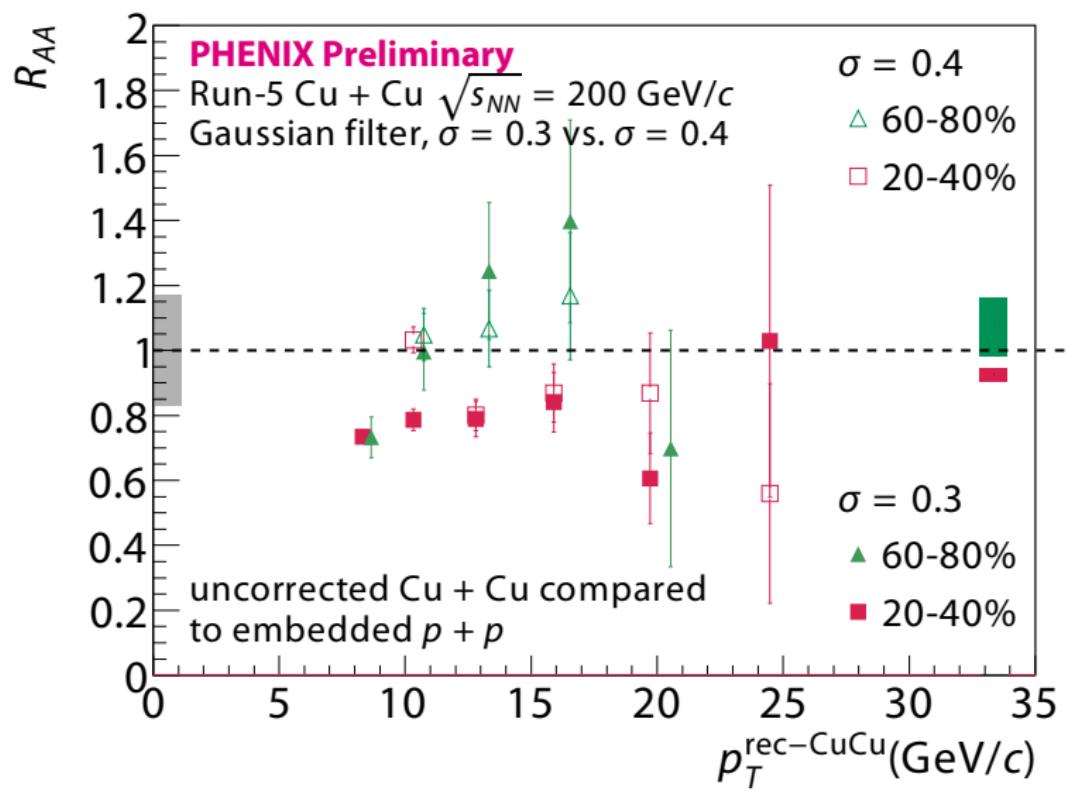
Run-5 Cu + Cu R_{AA} with $\sigma = 0.4$ (embedding)



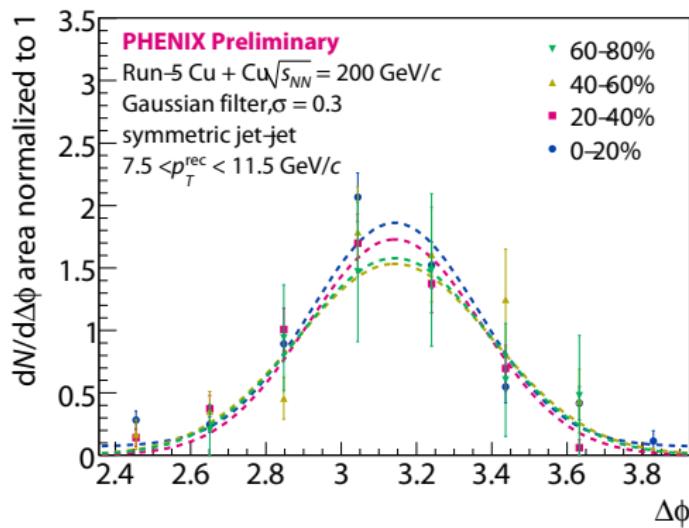
Run-5 Cu + Cu R_{AA} $\sigma = 0.3, 0.4$ comparison



Run-5 Cu + Cu R_{AA} $\sigma = 0.3, 0.4$ comparison



Cu + Cu jet-jet azimuthal correlation



- No centrality dependent broadening observed within sensitivity

Centrality	$\Delta\phi \approx \pi$ width σ
0–20%	0.223 ± 0.017
20–40%	0.231 ± 0.016
40–60%	0.260 ± 0.059
60–80%	0.253 ± 0.055

What makes a good detector for jets?

- Frequent occurrence of this sentence:

“<some single line reason> \Rightarrow well-suited for jets”
Complete misstatement of the problem!
- A good jet detector needs all of:
 - Hermiticity (not current PHENIX)
 - Fast readout (not current STAR)
 - Resolve individual hadronic showers (not current STAR) to remove track/cluster double counting, or get an HCal
 - Tracking beyond $\approx 10\text{--}20 \text{ GeV}$ (not current PHENIX, STAR), or get an HCal
 - Both EM and hadronic triggers (not current PHENIX, STAR)
 - Tracking is still needed for $D(z)$, etc. (not the Run-I D0)
- RHIC lacks a real detector for jet study
- How to fix this?

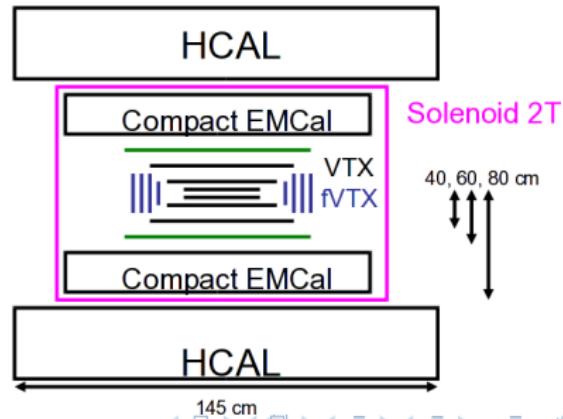
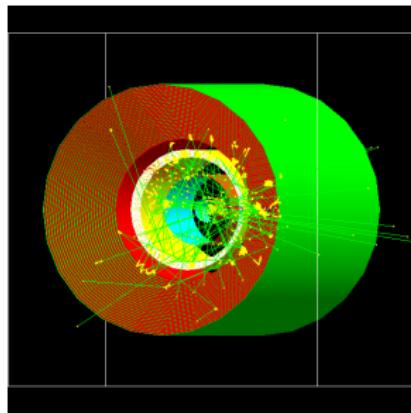
\Rightarrow The recurring theme is **hermiticity** (PHENIX will start to address this by Run-11) and the need for **HCal** (?)

Why a jet detector at RHIC?

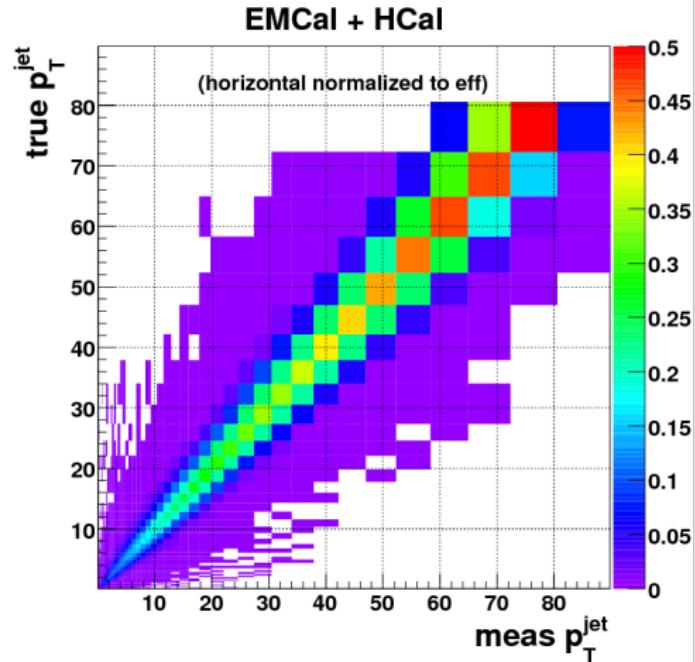
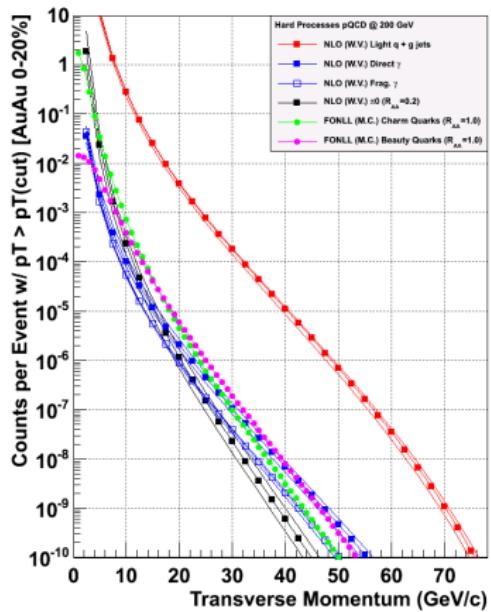
- Complementarity to the LHC
 - Difference in medium property
 - Probes a different mixture of quark-to- g jets
 - Probes a different jet E_T scale vs. LHC (where $E_T < 50$ GeV in 5.5 TeV Pb + Pb is going to be highly challenging)
 - Lack of 5.5 TeV $p + p, p + A$ will dominate the LHC's systematics for some time
- Why now?
 - Compact EMCal becomes available (compare PHENIX FOCAL)
 - Need to extend the physics studied, vs. repeated runs with the same detector
 - R&D overlap with the EIC
- But ...
 - $\Delta\varphi = 2\pi$ EMCal + HCal means PHENIX loses PID capability

PHENIX Upgrades for jets

- Early planning process to upgrade PHENIX as a dedicated jet detector
- A (even more) “Compact RHIC Solenoid”? (that makes CMS “bulky”)
- Conceptual design:
 - $\Delta\phi = 2\pi, \Delta\eta = 2$
 - Si vertex tracking (Run-11) + Compact SiW EMCal
 - $B = 2\text{ T}, R = 70\text{ cm}$ solenoid
 - HCal outside the field



Expected upgrade performance



- Light quark/g jets up to 70 GeV/c

- A highly “diagonal” energy scale

Summary & outlook I

- Fake jets must be removed even in Cu + Cu at $\sqrt{s_{NN}} = 200 \text{ GeV}$
- Gaussian filter with the Gaussian fake rejection ($\sigma_{\text{dis}} = 0.1$) a highly effective algorithm for jet reconstruction at RHIC energy
- PHENIX jet performance enhanced by the high-rate, accurate EMCal (though not ideal, given lack of HCal)
- Observation of strong jet suppression with $\sigma = 0.3$ and $\sigma = 0.4$, any difference is below our current uncertainties
- Observation of no significant $\Delta\phi$ broadening in jet–jet azimuthal correlation

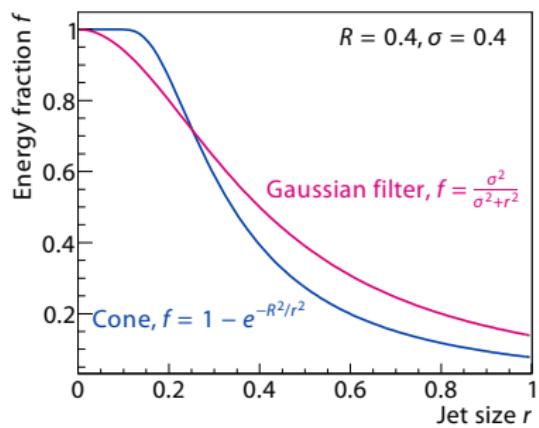
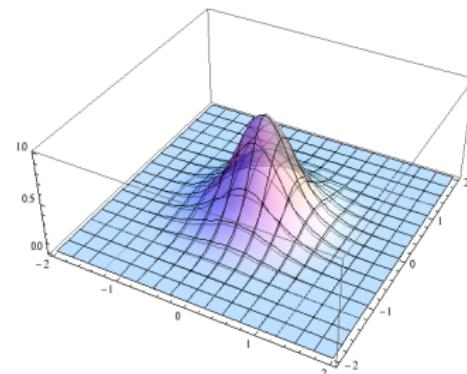
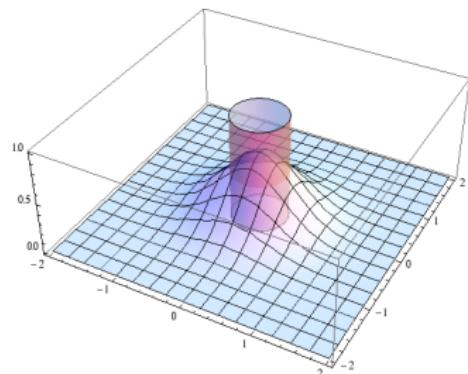
Summary & outlook II

- PHENIX is studying the medium using a uniquely suitable jet reconstruction algorithm with wide p_T range coverage, high efficiency, and low fake rate
- Obtained the first measurement of $p + p$ spectrum at RHIC upto $x \approx 0.6$
- Obtained the first measurement of $p + p$ jet fragmentation function at RHIC, inclusive and upto $z \approx 0.8$
- Obtained the first measurement of the dijet angular correlation in Cu + Cu collisions
- Obtained the first measurement of the jet R_{AA} in Cu + Cu collisions
- ... and still the only all-centrality heavy-ion jet measurement
- Cu + Cu a stepping stone in understanding heavy ion jet reconstruction
 - ⇒ We are intrigued by the current Cu + Cu results, and aim at understanding its physics implication before moving on to Au + Au
 - ⇒ Measurement of jet modification variables, e.g. fragmentation functions, j_T distributions, are in the works
- Future upgrades aim to rebuild PHENIX as a dedicated jet detector

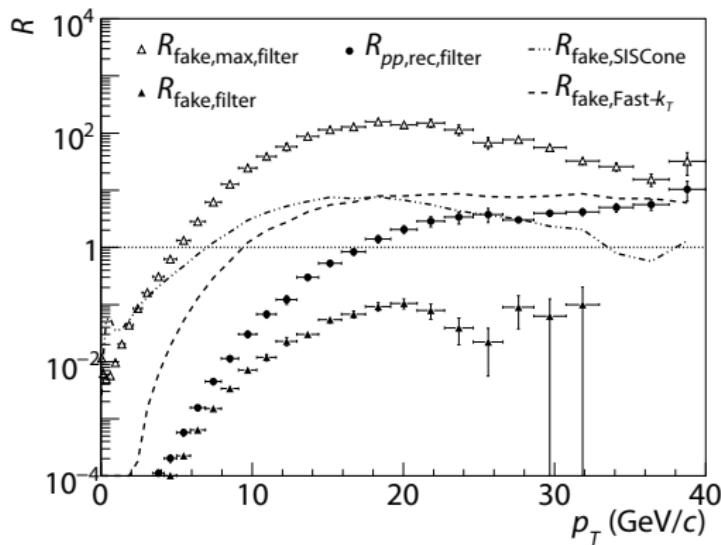
Part I

Backup

Jet energy collection

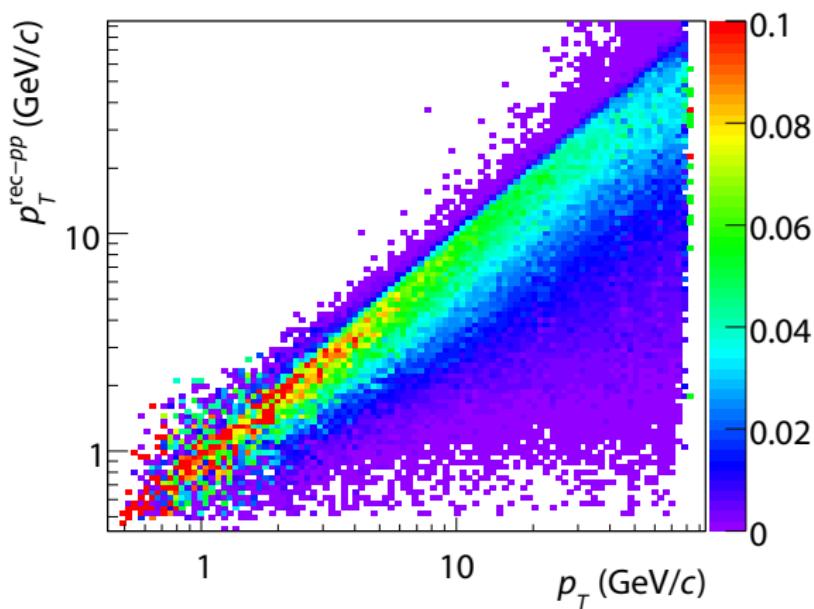


Fake rejection in HIJING central Au + Au



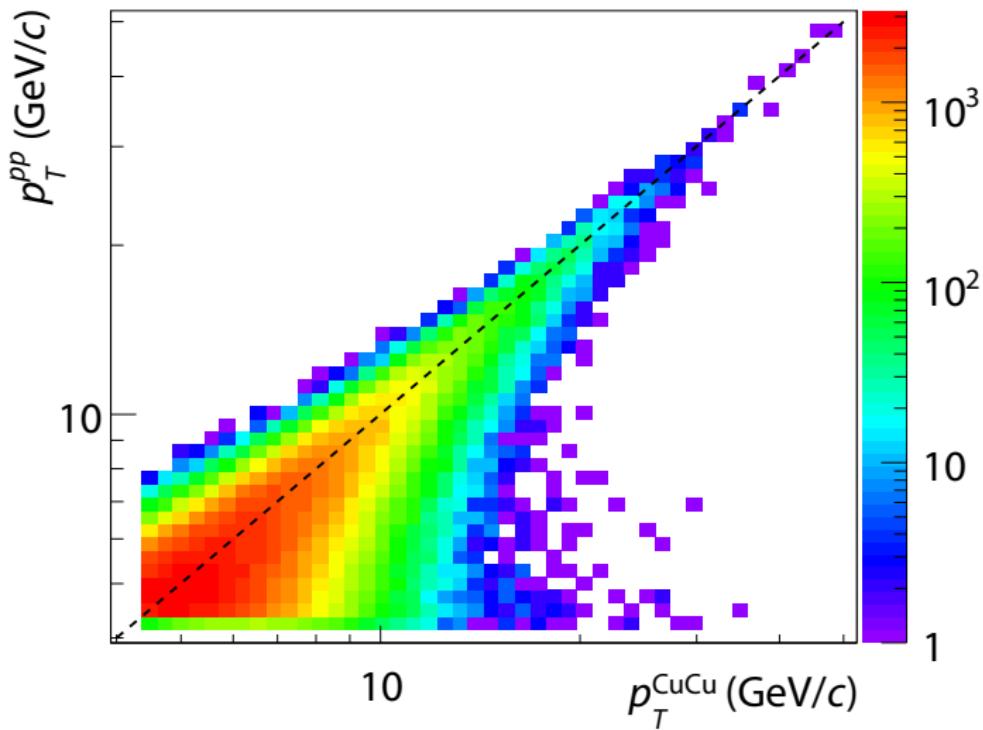
- Filter with Gaussian fake rejection compared to
 - k_\perp with $1/\sqrt{A}$ (Cacciari & Salam, Phys. Lett. B 659, 119, 2008)
 - SIScone with Σj_T (Grau *et al.*, ATLAS Collab., arXiv:0810.1219, 2008)
- Filter can efficiently fake reject even in worst-case assumption for Au + Au at RHIC energy

PHENIX jet energy scale

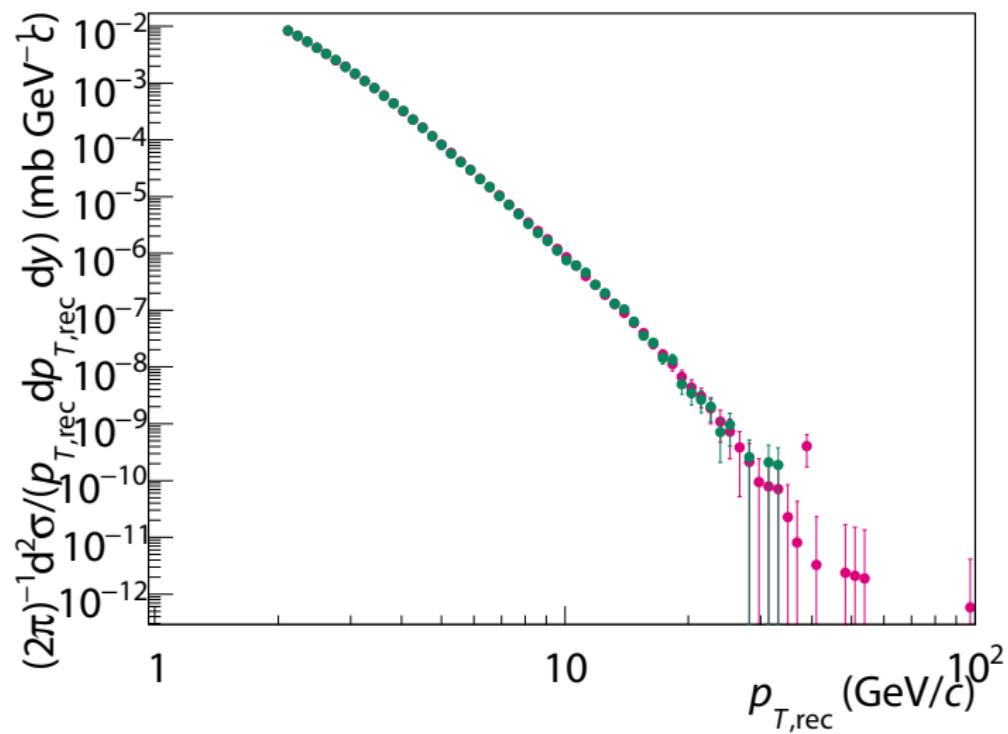


- PYTHIA + GEANT simulation with ~ 16 million events
- $p_T^{\text{rec-}pp} < p_T$ region dominated by n, K_L^0 energy loss

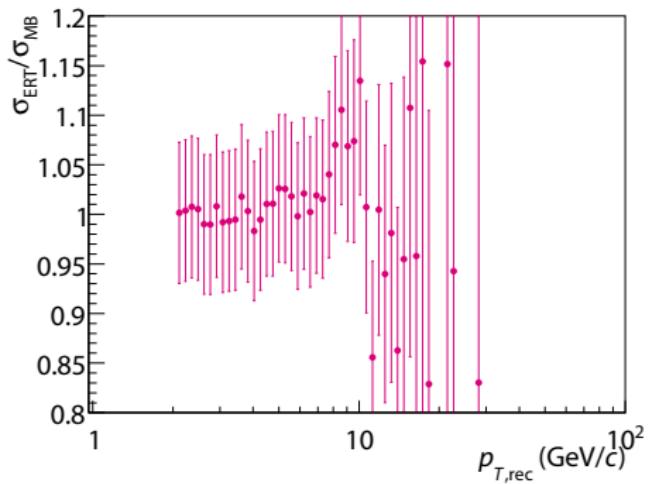
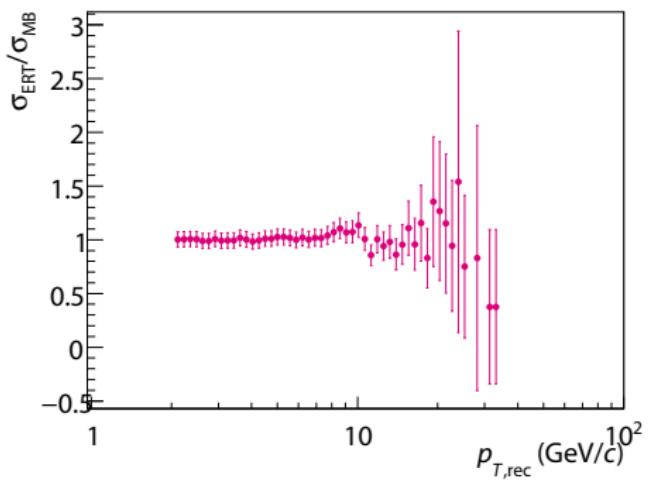
$p + p$ to Cu + Cu transfer matrix, 0–20% centrality



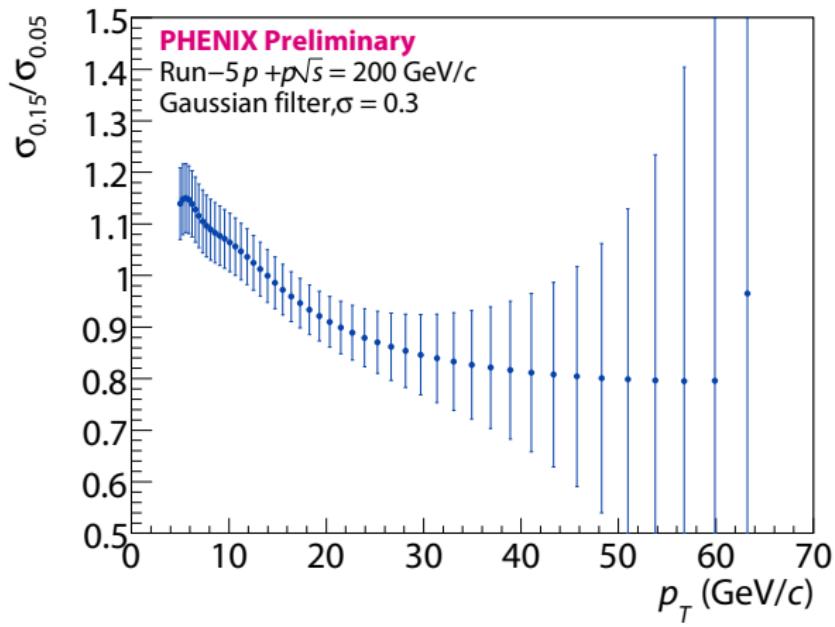
PHENIX ERT vs. minimum bias trigger



PHENIX ERT vs. minimum bias trigger



Effect of the PHENIX detector edge



Zeroth + first order sum p_T (Run-5 $p+p$ ERT)

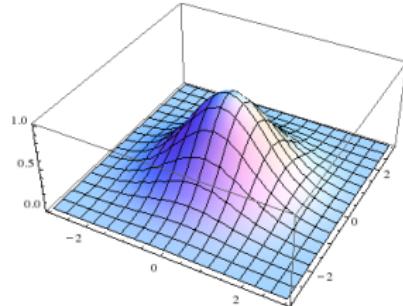
Flat (1D) integration:

$$\begin{aligned}\int dx p_T(x) &= \int dx e^{x^2/(2\sigma)} e^{-x^2/(2\sigma)} p_T(x) \\ &= \underbrace{\int dx e^{x^2/(2\sigma)} p_T(x)}_{p_T^0} + \underbrace{\frac{1}{2\sigma} \int dx x^2 e^{x^2/(2\sigma)} p_T(x)}_{p_T^1} + \dots\end{aligned}$$

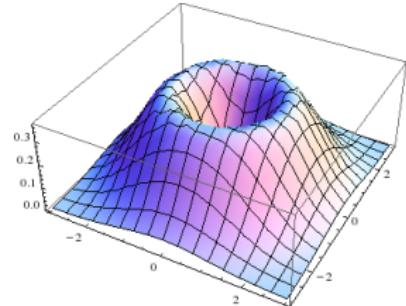
- $p_T^1 \ll p_T^0$ demonstrates that Gaussian filter is not losing significant amount of energy
- p_T^1 is closely related to the jet width, possible interesting physics

Zeroth + first order sum p_T (Run-5 $p + p$ ERT)

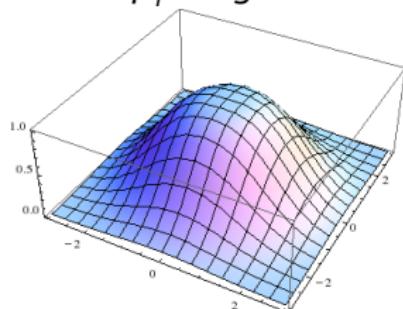
In pictures:



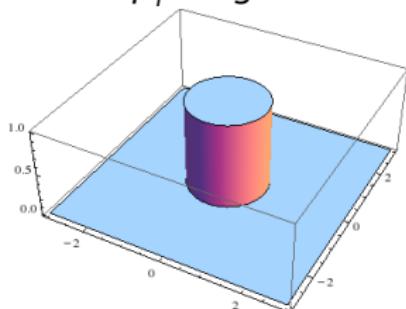
p_T^0 weight



p_T^1 weight



$p_T^0 + p_T^1$ weight



cone

Zeroth + first order sum p_T (Run-5 $p + p$ ERT)

